CONCRETE ENGINEERING

VOLUME I.

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PRACTICAL CONCRETE

BY

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FRED GIBSON, Esq.

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PREFACE.

THERE is a demand for a modern treatment of "Concrete Engineering." Rapid developments in the concrete industries make up-to-date reference books essential to the busy practical man.

This volume deals with the materials used in concrete, the designing of the mix, and the making, placing and curing. Later volumes will cover properties of concrete, special concretes, etc.

By slight repetition and a generous index the book is intended to be not only a text-book for students but a reference book for professional and practical men. Owing to current practice a few of the sections will not find immediate application, but they have been included for future requirements. The practicability of many of the ideas cited is assured by the fact that they refer to actual conditions in the field.

As the latest pertinent information from U.S.A. has been included, the reader should allow for the differences in units. These are mentioned in the text. A comparison of sieve openings appears on page 75.

Much has been drawn from the writer's articles, and he thanks the editors and publishers of the journals concerned. These and other sources of information are given in the Bibliography. Special mention should perhaps be made of the publications of the *Building Research Station* and of the *American Concrete Institute,* which are of inestimable value.

The reader will find numerous references to the *Specifications* of the *British Standards Institution* (by kind permission of the Institution). The following issues may be obtained from the offices of the Institution at 28 Victoria Street, London, S.W. 1, price 2s. net, or 2s. 2d. post free :—

No. 12, 1931. "Portland Cement."

No. 63, 1928. "Broken Stone and Chippings, Sizes of."

No. 146, 1932. "Portland Blast-furnace Cement."

No. 340, 1928. "Concrete Kerbs, Channels and Quadrants in Portland Cement."

No. 368, 1929. "Concrete Flags in Portland Cement."

Finally, the writer acknowledges his indebtedness to the directors of Messrs. G. & T. Earle, Ltd., Hull, for permission to use the results of laboratory tests, and wishes to thank Mr. W. T. Howe, Chief Chemist, and Mr. J. Hewick, Head Tester, of Messrs. G. & T. Earle, Ltd., for much valuable advice.

J. SINGLETON-GREEN.

HULL, *December*, 1932.

CONTENTS.

PAGE

CHAPTER I. **Normal Portland Cement,** 1

Modern Cements—Manufacture of Portland Cement—Properties—Tests—Composition—Strength—Setting and Hardening—Soundness — Delivery — Aeration — Hot Cement — Weight — " Balling "—Colour—Storage.

CHAPTER II. **Other Cements,** 39

Rapid-hardening Portland — Aluminous — White Portland — Coloured—" Super "—Blast-furnace—Roman—Cost of Cement—Consumption—Specification Suggestions.

CHAPTER III. **Types of Aggregates,** 59

General—Characteristics of Coarse Aggregates—Failures due to Aggregates—Occurrence of Aggregates—Artificial Aggregates.

CHAPTER IV. **Analysis of Aggregates,** 71

Samples—Types of Analysis—Grading of Aggregates, Fineness Modulus, Workability, Sand Content and Water Ratio.

CHAPTER V. **Wear of Aggregates and Concrete,** 85

Tests Required — Rocks — Gravel — Comparison of Attrition Results—Wear Tests on Concrete.

CHAPTER VI. **Miscellaneous Properties of Aggregates,** . . . 95

Cleanness—Weight—Flat Pieces—Moisture—Soundness Test—Particular Aggregates :—Broken Concrete, Chert, Glass, Minion, Sea Sands, Shaley Gravel, Shingle, Spar, Stone Sand—Specifications.

CHAPTER VII. **Admixtures,** 125

General—Colouring Materials, Dyes, Pigments—Pozzolanas—Miscellaneous Admixtures, Calcium Chloride, Lime, Waterproofing Admixtures.

PAGE

CHAPTER VIII. **Water and Impurities**, ... 158
General—Examples of Water—Effect of Humic Acid, Salts, Sea-water, Tannic Acid.

CHAPTER IX. **Designing Concrete**, ... 165
General—Importance of Water Content—Water Ratio—Design of Pavement Concrete—High Early Strength—Approximate Quantities.

CHAPTER X. **Proportions**, ... 191
Methods of Proportioning, Measuring Cement, Measuring Aggregates, Inundation—Moisture in Aggregates, Determining Moisture in Sands—Quantities.

CHAPTER XI. **Mixing and Placing**, ... 203
General, Hand-Mixing, Machine Mixing, Time of Mixing, Central Mixing, Suggested Specification for Mixing Concrete, Retempered Concrete—Placing, Concreting under Water—Consistency, Slump Test — Workability — Laitance — Bonding —Winter Work—Job Rules.

CHAPTER XII. **Curing**, ... 235
Importance—Laboratory Results—Surface Coatings—Pavement Results—Coloured Concrete—Hot Water Curing.

BIBLIOGRAPHY, ... 244

INDEX, ... 251

ADDENDUM.

Test results published since this volume went to press indicate that the bond between aluminous and Portland cements is not a good one. Therefore the results quoted on pages 230-1 (reference 131) should be considered in conjunction with the new data. Investigations carried out by K. E. Dorsch are reported on page 151 of *Concrete and Constructional Engineering*, Feb., 1933. Dorsch concludes that there is not a good bond, and suggests that "aluminous cement is unsuitable for use as a protective coating to prevent the attack of Portland cement concrete by salt solutions."

CONCRETE ENGINEERING.

Volume I.—PRACTICAL CONCRETE.

CHAPTER I.

NORMAL PORTLAND CEMENT.

MODERN CEMENTS.

Natural and Artificial Cements.—The numerous cements on the market to-day may be divided conveniently into two groups—natural and artificial. The natural cements, whilst still used occasionally for special jobs, are relatively unimportant, the bulk of concrete work now being carried out with the artificial cements. These latter may be divided into classes in various ways, but perhaps the most practical division from the engineer's point of view would be to regard them as " Portland " and " Non-Portland."

" Portland " Cement.—The name " Portland " was given to the material by its inventor, Joseph Aspdin, because, when set hard, it resembled the well-known Portland stone. Portland cement, as we now know it, is manufactured by mixing together calcareous and argillaceous materials, burning this mixture to a clinker, and grinding the clinker to a very fine powder.

Rapid-Hardening " Portland " Cement.—This sub-heading strictly is not grammatical, but the expression is now universally used and understood. The rapid-hardening

Portland cements are true Portland cements in every sense of the word—they are simply " super " Portland cements. Their chief characteristic is high early strength. There is no recognised standard specification for them, but it is hoped that this state of affairs will soon be remedied. Many engineers have drawn up their own specifications, and whilst this may be regarded as a favourable sign, it is perhaps unfortunate that numerous standards have been created. That this causes confusion is evident when it is mentioned that the writer has seen some of these " private " specifications for ordinary Portland cement which had higher minimum requirements than those in other specifications for rapid-hardening Portland cements.

Aluminous Cements.—These cements are quite different in their chemical composition from those just referred to. The principal raw material used is bauxite, and as this has to be imported, there is a corresponding increase in the price of the cement. There are other reasons for the relatively high price of aluminous cements, and the result is that the use of these cements is confined largely to work where speed is of the utmost importance. In such cases, the increased cost is justified.

White Cement.—White cement may or may not be a Portland cement. There are at least three white cements (which have been and are being used in this country) which are true Portland cements, namely, Atlas, Medusa and Snowcrete. The first two are imported from the United States of America, and have become well-established, whereas Snowcrete is a British product, and has been put on the market only recently. The user of one of these cements can be assured that, apart from the colour of his concrete, the results will be similar to those obtained when the ordinary grey Portland cement is used.

Portland Blast-Furnace Cement.—There is a British standard specification for this cement. Portland cement clinker, made as already indicated, is mixed with granulated blast-furnace slag, and these are then ground together, so that the two constituents are thoroughly and intimately mixed. The proportion of slag must not exceed 65 per cent. of the total quantity. The requirements for strength,

setting time and soundness are the same as those laid down in B.S.S. No. 12 for Portland Cement (1931 Edition).

Strengths.—Other things being equal, improved cements mean improved concrete, but full advantage is not always taken of this fact. Several instances have come to the writer's notice where concrete made on the job, without unusual precautions, has shown an average strength of 5,000 lbs. per square inch at twenty-eight days on 6-inch cubes, but a working stress of 600 lbs. per square inch has still been used. This stress is allowed by the London County Council regulations when the strength at twenty-eight days is 1,600 lbs. per square inch. Clearly there is a large margin of strength here which could be put to practical advantage in a variety of ways. The rapid-hardening cements give still higher strengths, particularly during the early stages of hardening, and it is believed that in many quarters the importance of this is not fully appreciated.

The Manufacture of Portland Cement.

The B.S. Specification describes Portland cement as an intimate mixture of calcareous and argillaceous materials, burnt at a clinkering temperature, the resultant clinker being ground to produce cement. In general these materials are represented by chalk and clay, but they may vary considerably. The calcareous material ranges from the hardest crystalline limestone to soft chalk ; the argillaceous material varies from hard shales down to river mud ; while in some districts stone or marl is found of almost the correct composition, necessitating but slight adjustment to produce a correct mixture.

There are two methods in general use in the manufacture of cement—the " wet " and the " dry " processes. Both methods are the same except as regards the treatment of the raw materials. In the *wet process* the raw materials are mixed and ground together with water, the resultant mixture being called " slurry," which is fed into the kiln. In the *dry process* the raw materials are mixed and ground in a dry state, this mixture being fed into the kiln. In

each case, after burning in the kiln, the resultant clinker is taken to the mills and ground to a fine powder.

It will be seen that there are three separate sections in the manufacture of cement,[1] involving

1. The Raw Mill Plant,
2. The Burning Plant,
3. The Cement Grinding Plant.

The Raw Mill Plant.—The crushed chalk is received at the raw mill in wagons and fed automatically into storage silos. Thence it is fed into ball mills, into which clay is admitted in a liquid state (the mixture of clay and water having been made previously in the wash mills). The product from the ball mills passes through sieving machines, which return the coarse particles to the ball mills and allow the finer material to pass to the tube mills for further grinding. After leaving the tube mills the product is again ground in mills containing metal grinding bodies, and then falls into a pit to be pumped to the storage tanks. In this state it is known as "slurry."

Many tests of fineness and percentage of carbonate of lime and of water are made by the chemists during this grinding process. The "slurry" is again tested in the storage tanks, which are so arranged that it can be pumped from one tank to another, in order to get an absolutely correct mixture. The chalk and clay are reduced to an impalpable fineness in a wet state, the intimate mixture ensuring complete chemical combination in the burning process. The arrangements have been brought to such a state of perfection that the finished "slurry," as fed to the kiln, does not vary more than one-tenth of 1 per cent. as regards the content of carbonate of lime, or 1 per cent. with regard to fineness through a 180-mesh sieve (32,400 holes per square inch).

The Burning Plant.—A rotary kiln is used, consisting of a long tube, lined with fire-brick, set at a slight angle, and rotating about once a minute. The "slurry" is automatically fed into one end of the kiln, while at the other end coal, dried and ground, is blown in by a fan.

The action inside the kiln is as follows :—As the "slurry"

meets the heat, the water is evaporated, and as it passes farther down the kiln it is decomposed by the more intense heat, and carbonic acid gas is liberated. The lime is then free to combine with the silica and alumina, a chemical combination which takes place as the material passes through the "burning zone," where the temperature is between 1,300° and 1,400° Centigrade, calcium silicates and aluminates being formed. The calcined product (the clinker) then falls from the kiln into a cooler, which consists of a rotating cylinder through which air is passing. This air, after cooling the clinker, passes into the kiln at a high temperature, and with the coal fan supplies the air necessary for the combustion of the coal.

When the clinker leaves the cooler it is ready for the third and final section of the manufacturing process, *i.e.*, to be ground into finished cement. Correct burning being the most important part of cement manufacture, the clinker is examined and tested at very frequent intervals.

Cement Grinding Plant.—There are two types of cement grinding mills. In some cases "combination mills" are used; these consist of long tubes divided into three or more compartments, the first compartment being filled with large steel balls, and the other compartments with smaller balls. In other cases two mills are used—firstly a preliminary grinder consisting of a drum containing large steel balls, secondly the finishing mills which are tube mills.

Properties of Portland Cement.

Variations.—Though strength is regarded as being of great importance, it should not be considered the only criterion by which quality is judged. There is not necessarily any relation between the 7-day or 28-day compressive strength of concrete and the ultimate durability. It is generally assumed that there is only one grade of Portland cement, whatever the work it has to do, and this has led to the use of a so-called "standard product" for all purposes.

The assumption tacitly made [2] by many investigators

that all cements which pass the requirements of a standard specification are of equal quality, is untenable. Certain types of cement are less sensitive to an excess of mixing water; others will produce a high early strength; still others will not give a high strength until after the lapse of months. As has long been recognised, the age of the cement is also a vital factor in affecting the activity and integrity of the constituents. It cannot, then, be fairly assumed that all types of cement produce concrete of equal permanence.

The continual use of the B.S. Specifications over a long period of years had led to the belief that if two cements pass the strength tests equally well, one is as good as the other; but this is not necessarily so. It is essential to *dispel* the erroneous idea [3] that there is such a thing as a *standard* Portland cement. It has been shown that Portland cement develops other properties than those of hardening and acquiring strength, and some of them, such as volume change and heat developed during the reaction with water, may be so paramount in special cases as practically to force the ignoring of strength.

This is the next logical development in the study of concrete, namely, that " Portland cement " must be regarded as a variable and not a constant in all the problems concerned. Such a statement is fundamental and revolutionary. It means, among other things, that many of the research conclusions, which have been drawn on the assumption that all Portland cements are alike, are possibly erroneous. The urgency of studying all the properties of concrete as resulting in a major degree from the quality of the cement cannot be over-stressed. There is no constituent of concrete more worthy of study, and yet, as an essential variable, it has been studied less than any other of the components.

Essential Requirements.—The quality of the cement should not be lower than that laid down by the B.S. Specification, and generally it will be an advantage to use a cement which is far better than that which only just passes these requirements. The use of a high-class cement is always an economy. For average conditions a cement must have the following properties :—

1. Capacity for setting, with a fairly slow setting time to allow for mixing and placing.
2. Strength when hardened.
3. Soundness, *i.e.*, freedom from any tendency to expand.

Other properties are mentioned in the B.S. Specification, but it is clear that items such as " hydraulic modulus " are not of immediate concern to the user of cement. He wants something which will set, become strong, and remain sound, but, as already mentioned, other properties have to be considered in many cases.

Tests for Cement.

B.S. Tests.—The following summary is reproduced by kind permission of the *British Standards Institution.*[4]

" (*a*) *Fineness.*—Residue on 170-mesh sieve not to exceed 10 per cent.
Residue on 72-mesh sieve not to exceed 1 per cent.

" (*b*) *Chemical Composition.*
1. The hydraulic modulus (or ratio of lime to silica and alumina) to be not greater than 3·0 and not less than 2·0.
2. Loss on ignition not to exceed 3 per cent. (4 per cent. in hot climates).
3. Insoluble residue not to exceed 1·0 per cent.
4. Magnesia ,, ,, 4·0 ,, ,,
5. Total sulphur calculated as sulphuric anhydride not to exceed 2·75 per cent.

" (*c*) *Tensile Strength (Neat).*—Not less than 600 lbs. per square inch at 7 days. This is an optional test.

" (*d*) *Tensile Strength (Mortar).*—3 : 1 sand-cement mortar, not less than 300 lbs. per square inch at 3 days, and 375 lbs. per square inch at 7 days. Strength at 7 days to show an increase over that at 3 days.

" (*e*) *Setting Time.*—Normal-setting cement : Initial set of not less than 30 minutes, and final set of not more than 10 hours.
Quick-setting cement : Initial set of not less than 5 minutes and final set of not more than 30 minutes.

" (*f*) *Soundness.*—Expansion by the Chatelier Test to be not more than 10 mm., or 5 mm. after 7 days' aeration. Time of boiling, 3 hours."

Old Specifications for Cement.—The following table shows the rise of the British Standard Specification for Portland cement from the first issue in December, 1904, to the most recent specification issued in November, 1931. Even the latest specification falls very far short of many well-known

brands of superior Portland cement, and the introduction of rapid-hardening cements has brought about quite a different set of conditions.

B.S. SPECIFICATIONS FOR PORTLAND CEMENT.

YEAR.	REQUIREMENTS.					
	Tensile Strengths in Lbs./Sq. In.					Residue on 180-mesh Sieve, per cent.
	Neat.		3 : 1 Mortar.			
	7 Days.	28 Days.	3 Days.	7 Days.	28 Days.	
1904	400	500	...	120	225	22·5
1907	400	500	...	150	250	18
1910	400	500	...	150	250	18
1915	450	538	...	200	250	14
1920	450	538	...	200	250	14
1925	600	...	...	325	356	10
1931	...	...	300	375	...	10 (170-mesh).

Samples of Cement.—Clauses 2, 3, 4 and 5 of *B.S.S. No. 12* give details of the sampling which should be done. Each sample should consist of equal portions taken from 12 bags, and should weigh not less than 10 lbs. Such a sample should be taken for every 250 tons, when dealing with large quantities. Most bags (whether jute or paper) are now of the valve type, and a sample of the cement may easily be taken by pushing a tube through the valve, holding the hand tight against the end of the tube, and withdrawing. In this way the bag is not opened.

Testing.—Tests are usually carried out in accordance with *B.S.S. No. 12*, but, in addition to the tests mentioned therein, there are a few simple tests which can readily be carried out in the field. Cost of tests, non-compliance with tests, and copies of tests, are dealt with in Clauses 6, 14 and 15.

Cement testing is a skilled job, and the work should always be entrusted to a trained man, or to a laboratory specialising in this kind of work. Untrained testers will

obtain varying results which at best are open to suspicion, and which may even lead to serious errors. For the ordinary job, however, the laboratory testing of cement is not necessary if the supplies are from a firm of repute. Where tests are considered advisable, truly representative samples should be submitted to qualified men.

Quantities for Tests.—As a guide to the quantities of materials required in tests the following figures are given :—

Small Setting Pat.— 4 oz. cement,
1 ,, water.

Neat Tensile Briquette.— 12 oz. cement,
2·7 oz. water ($22\frac{1}{2}$ per cent. of the cement).

To make two briquettes.

Mortar Tensile Briquette.—12 oz. sand,
4 ,, cement,
$1\frac{1}{4}$ oz. water (8 per cent. of the sand and cement).

To make two briquettes.

Neat Compression Cube.— 1 lb. 10 oz. cement,
5·4 oz. water.

To make one cube $2\frac{3}{4}''$ side.

Mortar Compression Cube.— 1 lb. 8 oz. sand,
8 oz. cement,
2·56 oz. water.

To make one cube $2\frac{3}{4}''$ side.

Fineness.—Reference to the various *B.S. Specifications* for fineness will show that the residue on the 180-mesh sieve, which in 1904 was 22·5 per cent., has dropped to a maximum of 10 per cent. Increased fineness of grinding means increased strength and greater covering power.

This is, therefore, an important point to consider when buying cement. Roughly, it may be said that, for each one per cent. reduction in the residue on the 180-mesh sieve, the weight of the cement per cubic foot (for standardised methods of measuring) is reduced by one pound. A cement just passing the specification with 10 per cent. residue can be taken as weighing 90 lbs. per cubic foot, according to the figure laid down by the London County Council in their Regulations. "*Ferrocrete*," a rapid-hardening cement having a residue of about 0·5 per cent., may be taken as weighing 80 lbs. per cubic foot. This latter is allowed by *B.S.S. No. 340* for kerbs, etc.

The following conclusions, based on a series of tests, appeared in a Bulletin issued by the *U.S. Bureau of Standards* in 1925 :—

> "No retrogression is shown in the compressive strength of the concretes at the end of the 10-year period. In general, the fineness of the cement increased the strength of the concrete. All cements do not give the same increase in strength with the same increase in fineness. The effect of fineness of cement on the strength of concrete diminishes with age. The 1 : 2 : 4 mixes show better increases of strength with the same increase in fineness than do the 1 : 3 : 6 mixes."

The following conclusions are summarised from a Paper [5] by D. A. Abrams :—

1. There is no necessary relation between the strength of concrete and the fineness of the cement, if different cements are considered.

2. Fine grinding of cement is more effective in increasing the strength of lean mixtures than rich ones.

3. Fine grinding of cement is more effective in increasing the strength of concrete at seven days than at ages of twenty-eight days to one year.

4. For the usual range of consistencies the effect of fineness of cement is independent of the consistency of the concrete. The rate of increase in strength with fineness is lowered for very wet mixtures.

5. The decreased benefit of fine grinding of cement with the age of the concrete does not bear out accepted opinion that the coarser particles of cement do not hydrate, but indicates that the principal result of finer grinding is to hasten the early hardening of the concrete.

6. For the richer mixtures and the consistency necessary for building construction, the fineness of the cement has no appreciable effect on the workability of concrete as determined by the "slump" test. For leaner mixtures and wetter consistencies the finer cements showed a somewhat greater "slump" than the coarser cements.

7. The time of setting of the cement is shortened with finer grinding.

8. The unit weight of cement decreases with fineness. For the cements used in these tests the weight varied from 76 (residue of 2·4 per cent.) to 108 lbs. per cubic foot (residue 43·3 per cent.). For the usual range in fineness the weight is lowered about $\frac{3}{4}$ lb. per cubic foot for each 1 per cent. reduction in the residue on the No. 200 sieve.

9. In using 94 lbs. per cubic foot as a uniform basis for proportioning the cements in these tests, the actual volume of cement in a batch of the same mix varies about 35 per cent. If the mixtures had been proportioned in a manner that would have given a uniform volume of cement, the resulting concrete strength would not have been so favourable to the finer cements.

10. The fineness of cement has no appreciable effect on the yield or density of concrete.

11. Concrete of all mixes and consistencies showed expansion in damp sand or water storage and contraction in air.

12. The change in length of concrete specimens stored in air or water is independent of the fineness of the cement and the consistency of the concrete. The lean concretes are slightly less affected than the rich mixtures.

13. The type of aggregate has little or no influence on the relative effect of fineness of cement on the strength of concrete.

It was reported in *Building Science Abstract 1122*, June, 1929, that in the case of the rapid-hardening Portlands, it may be said that 0·5 per cent. is retained on the 180-mesh sieve, 1·0 per cent. is retained on the 200-mesh sieve but passes the 180-mesh sieve, while 98·5 per cent. passes the 200-mesh sieve, and, of this, about 80 per cent. can be separated by means of a flourometer. Of these fractions, only the flour becomes immediately active when gauged. Of the fraction passing the 200-mesh sieve only the flour contributes to the very early strength of the cement, while the larger fractions are slow in their hydraulic reactivity. For these reasons it is thought that the percentage of sieve residue is not a criterion either of the fineness or of the constructional value of a cement, and that the correct method of determining cement fineness is one based on the proportion of flour present. Various devices for measuring this percentage have been developed, but are found to give inconcordant results. The *Associated Portland Cement Manufacturers, Ltd.*, have adopted a standard air elutriator, and a "standard flour" content, the flour being the material elutriated by air at a definite velocity of 21 feet per minute. It is found that the average particle diameter of this flour is about 0·01 mm. and that this is constant when the flour is separated at that velocity.

It is interesting to note that, for certain processes, some manufacturers prefer the coarser cements. For instance, a coarse cement has sometimes been found preferable for concrete flags made by hydraulic pressure, the explanation put forward being that the finer cement holds the water, and causes an inferior product. Again, the manufacturers of spun concrete may find coarse grinding an advantage. It is not wise, however, to be dogmatic on such a subject, and there are so many variables to consider that only actual tests will supply the requisite information.

Composition of Cement.

To deal with the composition of cement is rather outside the scope of this book. Speaking broadly, aluminous cement

contains the same constituents as Portland cement, but in different proportions. The comparison is approximately as follows :—

Constituent.	Portland Cement, per cent.	Aluminous Cement. per cent.
Silica, ...	22	5-15
Alumina, . . .	7	35-45
Iron Oxide, . . .	3	5-15
Lime, ...	63	35-45

Gypsum in Cement.—The following explanation is given by R. K. Meade, in the third edition of his book "*Portland Cement*," as to why low *gypsum* content may be the indirect cause of expansion and consequent checking.

All authorities seem to agree that the chief cause of expansion is the presence of free or unstable lime over and above a certain limit. This free lime slakes *after* the cement itself has hardened or set, causing the test piece to warp and check from the expansion set up by the slaking. The object of all tests for soundness is, therefore, to ascertain if the maximum of free lime that may safely be present has been exceeded.

Pats allowed to harden in steam or hot water will often pass the boiling test where pats hardened in air will not. It must be remembered that checking is caused by slaking (of free lime) *after* the pats are fully hardened. If the pats are placed in steam to harden, the warm moist atmosphere merely accelerates the slaking of the lime, doing the work before the pat hardens. The addition of sulphates, either as gypsum or plaster of Paris, aids the cement in standing the boiling test, probably because it delays the set until after the lime has slaked.

Since gypsum tends to delay the set until after the free lime has slaked, it logically follows that a low gypsum content will permit an earlier set, as a result of which the pat of cement may harden before the lime has all slaked.

Then, when slaking subsequently occurs, expansion and checking are the likely results.

Hydraulic Modulus.—The hydraulic modulus is the ratio of lime to silica and alumina in Portland cement. The following is part of the clause in *B.S.S. No. 12,* 1931, dealing with the point :—

> *B.S.S. No. 12, 1931, Clause 9* (*part*).—" The cement shall comply with the following conditions as to its chemical composition. The proportion of lime, after deduction of the proportion necessary to combine with the sulphuric anhydride present, to silica and alumina when calculated (in chemical equivalents) by the formula $CaO/(SiO_2 + Al_2O_3)$ shall not be greater than 3·0 or less than 2·0."

However, there is no need to worry about this matter, as any British cement will comply with this requirement. If tests are insisted upon they should be carried out by one of the recognised testing firms.

Strength of Cement.

Use of Standard Sand.—There is a somewhat general idea [6] that tensile or crushing test results on cement made with standard sand represent the best results of which the cement is capable. This is erroneous. Such tests do not give the highest results which can be got out of the cement, but give results which are standardised, and therefore comparable as obtained by different operators. The crushing strength, especially, of concrete or mortar, depends largely upon the size and character of the aggregate, the absence or presence of dust, clay matter and other things, and the density of the mass. The use of standard sand merely gives results which are comparable, and which represent the strength of a cement when tested under certain conditions and with an aggregate of a definite size and character.

The standard sands employed and specified in different

countries vary in size to some extent, as shown in the following table :—

Sand.	Residue on Sieves, per cent.	
	20-Mesh.	30-Mesh.
German . . .	17·4	100
French, . . .	91·0	100
Austrian, . . .	0	72·8
American, . . .	0	100
English, . . .	0	100

These differences in size of grain doubtless have their effect upon the results obtained.

Strength Results.—Although a cement passing the *B.S. Specification* will give satisfactory results, it is possible to obtain a cement of much higher quality, and the strengths which may be expected are indicated in the following table :—

Test.	*B.S.S. No. 12*, lbs./sq. in.	Results *Possible* with a Good Cement.
7-days neat (optional) tension, .	600	1,080
3-days mortar 3 : 1 tension, .	300	530
7- ,, ,, ,, ,, .	375	700
7- ,, ,, ,, compression,	...	7,900
28- ,, ,, ,, ,,	...	8,700

Standard Aggregate.—To compare different cements it is sometimes convenient to use a " standard " aggregate and make up cubes for compression tests. The following details refer to test cubes made up by a well-known cement firm.

The "Standard Aggregate" consists of two parts by weight of coarse aggregate and one part of fine aggregate.

Voids in coarse aggregate, . .	32 per cent.
,, fine ,, . .	32 ,,
,, standard ,, . .	23·5 ,,
Weight per cu. ft. coarse aggregate, .	110·5 lbs.
,, ,, ,, fine ,, .	110·5 ,,
,, ,, ,, standard ,, .	124·0 ,,

It requires 112·5 volumes of coarse and fine aggregate measured separately in the proportions of 2 : 1 to produce 100 volumes of standard aggregate.

In making up the concrete tests, proportions are by volume, but the actual materials for the tests are by weight, the weights being calculated from the weights per cubic foot. Cement is assumed to weigh 84 lbs. per cubic foot.

In making up any batch, the grades in the aggregate are weighed out separately to produce an amount of aggregate only slightly in excess of the requirements for the given moulds. This is done to minimise segregation. The water of the mixture is measured and the consistency of the mix is gauged by the "slump test," a one-inch "slump" being obtained. The test pieces are normally 6-inch cubes filled in three layers, and stored in damp sand until broken.

Setting and Hardening of Cement.

It is necessary to differentiate between "setting" and "hardening," and the writer suggests that the word "quick" be always used with "setting," and the word "rapid" with "hardening." A quick-setting cement sets in less than half-an-hour. "Hardening" refers to what happens after the "setting" period. There is no definite relation between "setting" and "hardening," and a cement may be :—

1. Slow-setting and slow-hardening,
2. Slow-setting and rapid-hardening,
3. Quick-setting and slow-hardening,
4. Quick-setting and rapid-hardening.

Cement and water form a paste which remains plastic for a short time, but begins to stiffen or "set" as the chemical reactions proceed. Soon the mass loses its plasticity, and if it is then disturbed there will be a serious loss of strength. The chemical actions continue after setting, and the mass gains in strength and hardness (see "False Set," p. 18).

Setting Time.—The setting period is affected materially by the temperature, and in warm weather the set is hastened appreciably. In cold weather the set takes place very slowly, particularly at temperatures approaching freezing-point.

If the initial set be lengthened, by any method, the final set is lengthened by approximately the same amount. The effect of pressure on the setting time is interesting. A sample of "*Ferrocrete*" which gave 110 minutes initial set and 170 minutes final set, gave 25 minutes initial set and 90 minutes final set under a pressure of 125 lbs. per square inch.

When determining the setting time of a cement in the laboratory it is important to have absolutely standard conditions, since :—

1. The time of mixing affects results. The longer the mixing period, the slower the set.
2. The amount of work done on the pat affects the result. The more work done on the pat, the slower the set.
3. Increase in the proportion of water lengthens the setting time.
4. The temperature of the air affects results. The colder the air, the slower the set.
5. The temperature of the water affects results. The colder the water, the slower the set.
6. The moisture in the air during setting affects the result. The greater the humidity, the slower the set.

It is evident that without standard testing conditions the results obtained may be quite misleading.

In a Paper entitled "Errors in Determining the Time of Setting of Cement," read before the *American Society*

for Testing Materials, G. M. Williams states that the time of setting of cement is affected by a number of factors, which, acting together or separately, account for the variable results obtained on the same material in different laboratories. The variation in results obtained in his investigation were only to be considered as characteristic of the range which may be obtained in practice. The following factors may cause errors of considerable magnitude :

1. Variation in the amount of work done on the material may cause a difference of more than two hours in the time of initial setting and cause a normal cement to appear quick-setting.
2. Variation in atmospheric moisture or humidity of storage during the setting period may cause the initial time of setting to vary as much as two hours.
3. Variation in atmospheric heat or temperature of storage during the setting period may vary the time of setting as much as one or two hours.

The results of the tests indicate that, even when all external factors are controlled, neither the Vicat nor the Gillmore method will give results consistent enough to justify the reporting of such figures within the limits of a few minutes.

Y. Shimizu, of the Tohoku Imperial University, Japan, has described an electrical method for measuring the setting time of cement. He found that the electrical conductivity of a cement paste decreased markedly at the moment of final set, and suggested that this property be used to determine the time of setting.

False Set.—A phenomenon known as " false set " occurs occasionally with modern cements, mostly with those which are very finely ground. The cement stiffens and appears to set, but does not actually do so, and it is necessary to distinguish between the " false set " of an otherwise normal-setting cement, and the genuine set of a quick-setting cement. Cement which has just reached a " false set " can be re-mixed without the addition of more water, but a quick-setting cement which has just set would break up on remixing, and more water would have to be added.

An expert cement tester can tell by the look of a pat whether the set is genuine or not. There is a difference in the appearance, as with a genuine set the pat goes dull and has an appearance which is definitely different from that of the false-setting pat. With the " Vicat needle test " the false set would appear as a true set, but pressure with the thumb nail will show that a pat having a false set is softer than one having a genuine set. This suggests that the Vicat needle test requires improvement.

Field Test for Setting and Hardening.—A simple way of testing the setting and hardening of cement on the job is to make a stiff paste of the cement and water and form a pat 3 inches in diameter and 1 inch thick on some impervious material such as glass. The pat should be kept under cover at a moderate temperature and not allowed to dry-out too quickly. If the temperature is below 45° F. a slower rate of hardening should be expected. If the cement is satisfactory the pat will resist the pressure of the thumb nail in 18 to 24 hours, and it will be difficult to break it with the fingers after 48 hours.

Heat during Setting.—The setting and hardening of ordinary cement concrete is a chemical process, during which heat is evolved. There will be a slight rise of temperature when setting occurs, but in small sections it may not be apparent, owing to the ready dissipation of the heat evolved. In the case of ordinary Portland cement the rise in temperature is not usually great, but in certain instances (as in large concrete dams) the heat evolved is conserved for extremely long periods, a temperature of 100° F. often being reached. With rapid-hardening Portland cement the rise in temperature is greater, and this is one reason why this material is of value in cold weather.

The heat produced during the setting and hardening of aluminous cement concrete is very great, and in the case of large masses which do not get much chance to dissipate their heat the temperature gets too high for good results. This can be counteracted by the copious application of water (after setting) to the face of the concrete.

Temperature and Setting.—The heat generated [7] during the setting of concrete has attracted the attention of many

for a considerable number of years. Further, those who have studied the question have properly connected it with shrinkage, since if the concrete has reached a temperature during setting above that of the surrounding atmosphere, contraction must result during later cooling, unless the concrete is of the rather unusual yet possible kind that would expand during hardening.

A very extended discussion of this subject appeared as a result of a Paper by Gowen [8] in the *Transactions of the American Society of Civil Engineers* in 1908. Merriman, in discussing the Paper, makes a statement which should be clearly borne in mind on account of its significance regarding the magnitude of the temperature change and because of coupling this with induced tensile stress. Merriman says " in any masonry dam the maximum range in temperature which causes tensile stresses in the masonry is the difference between the temperature at which the cement assumes set and the cement temperature which may subsequently be reached." This brief statement clearly indicates the importance of the heat evolved during setting. Since the maximum temperature which may be reached after hard set has taken place may be 50° F. higher than the surrounding normal temperature, and since further in many cases the atmospheric temperature range may be 100° F., it follows that volume changes (shrinkage) may be induced by a temperature drop of 100° to 150° F.

By making a suitable allowance for radiation, a curve can be drawn showing what the temperature rise would be with no radiation. This curve [9] becomes horizontal when the setting is completed. Fig. 1 gives some typical curves, so corrected, for ordinary Portland, rapid-hardening Portland and aluminous cements. It will be seen that the very rapid setting of the aluminous is well shown, and also the greater speed of setting of the rapid-hardening as compared with the ordinary Portland. These curves are taken from some work done by H. D. Morgan and C. M. Peppiatt, research students at the *City and Guilds Engineering College*, under S. M. Dixon. It will be seen that temperature rises of about 100° C. are obtainable with neat cements.

With concretes, lower values would be obtained, depending on the mixture, but with 1 : 2 : 4 mixture temperature rises of about 40° C. are obtainable.

Now, in actual practice, only a fraction of such emperature rises are shown, owing to radiation, etc., but the following instances may be of interest. In an 8-feet thick retaining wall in the Bank of England rebuilding, Faber

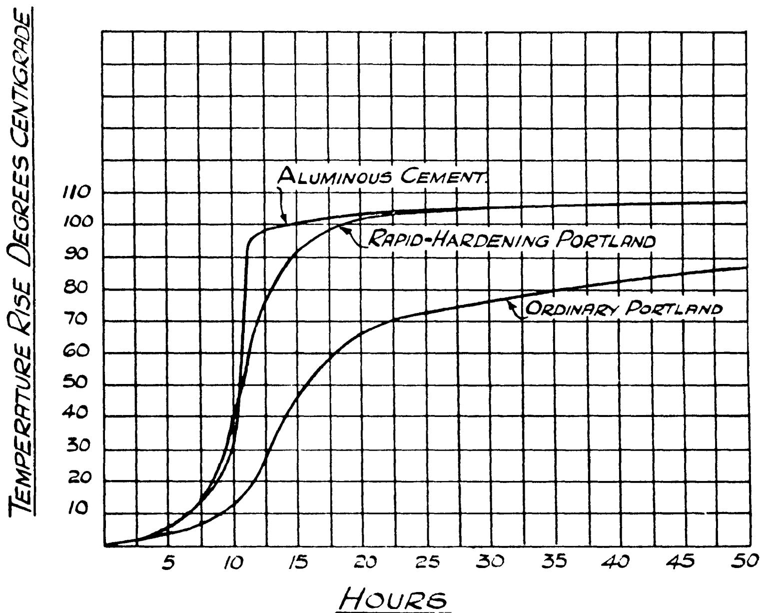

Fig. 1.—Temperature and Setting of Cement.

measured a rise of 50° F. (28° C.) (*i.e.*, from 50° F. to 100° F.) which occurred in three days after placing. In this case the concrete was about 1 : 1·6 : 3·2. One face of the wall was against earth and the other inside centering. In a large bridge pier in the United States, a temperature rise of 70° F. (39° C.) was recorded after 15 days (from 46° F. to 116° F.). Some large blocks of rich concrete, made by Faber for special purposes, rose in temperature from 40° F.

to 145° F., a rise of 105° F. (58° C.). In ordinary concrete floors and walls, the radiating surfaces are generally so great relative to the mass of material producing heat that only small temperature-rises are produced.

Faber has in frosty weather made use of this property of heat production by placing the concrete at 60° F. (by heating the sand, stone and water by steam) and then covering with insulating materials. The initial temperature being sufficient to start energetic setting, the heat produced by the latter process kept the concrete from cooling until it was set hard and free from danger.

Quickening-up.—The "quickening-up" of cement,[10] by which is meant the spontaneous change from a normal slow setting-time to a very quick setting-time, is a difficulty that has caused anxious moments to cement manufacturers and cement users. It has happened that consignments of cement have left cement works with normal setting properties and when put into use some weeks later have been found to set hard in a few minutes. No generally-accepted explanation of this change in setting properties has been presented, and although it is an occurrence that now rarely happens, the difficulty has been evaded rather than remedied.

When the change to quick-setting has taken place it has usually been with a cement which had medium setting properties, viz., a final set of from thirty minutes to three hours, and the evasion of the difficulty has been helped by the deletion of the "medium setting" grade from the British Standard Specification for Cement.

For general use, manufacturers now produce cement with a final set of between three and six hours, and with the proper precautions in manufacture there is practically no risk of such a cement becoming quicker-setting with time. The abandonment of the medium-setting grade of cement has been no disadvantage, because in most concrete work the time of setting (so long as it is known) is of small importance compared with the speed of hardening, and this latter property appears to have no connection with setting properties as ascertained by specification tests.

Soundness of Cement.

The *B.S.S.* test for soundness is by the well-known "Chatelier test," and the maximum expansion allowed is 10 mm., or 5 mm. after 7 days' aeration. This limit is considered by many people to be too high, as a good modern cement rarely shows an expansion of more than 1 or 2 mm.

In the field it is not always convenient to carry out the Chatelier test, and a simple test may be made as follows :—Sufficient cement should be mixed with water (about $22\frac{1}{2}$ per cent. by weight of the cement) to make a pat $\frac{1}{2}$ inch in thickness and 4 inches in diameter. It is an advantage to thin out the pat at the edge as cracks will be more evident. The pat should be placed on a piece of glass, iron, slate or other non-absorbent material and left for 24 hours in a damp box, after which it should be kept in clean still water. It can be inspected periodically for any signs of unsoundness. The test may be made more stringent by boiling the pat for a few hours (after it has hardened). Even after such drastic treatment a good cement will show few, if any, marks or cracks.

The following have been suggested as causes of unsoundness :—

1. Use of too high a proportion of lime in the raw materials used in the manufacture of the cement. Hydration of the lime causes expansion. We rarely get this now, owing to fine grinding (see 3).
2. Under-burning of the clinker.
3. Grinding too coarse. Though this has been shown sometimes to cause a high expansion in the Chatelier test, it is not definitely established that coarse grinding would cause disintegration in concrete. Limit of lime content of cement "slurry" depends (among other things) on the degree of grinding the cement is to get, and on the degree of grinding of the "slurry" itself.
4. Presence of too much magnesia. This will cause disintegration, even after many years.

Cold Plunge Test.—Several years ago a proposed method of testing the soundness of Portland cement was introduced

called the "immediate immersion" or "cold plunge" test. It consisted of the immediate immersion of a small pat of the cement in cold water, as soon as gauged. After some hours, when the cement had set, unsoundness was looked for as cracking of the surface of the pat, or, more particularly, in distortion, which sometimes separated the pat from the glass on which it was placed.

In Paper No. 3829, *Proc. Inst. C.E.*, vol. 177, A. C. Davis stated it would appear that as a broad general rule only slow-setting cements are affected by the "cold plunge" tests, and this without the quality of the cement being called into account. In this test defects might be separately or collectively occasioned by—

(*a*) Under- or over-burning of the clinker, which may in its turn be due to over- or under-liming in the raw materials, or to inefficient grinding or mixing in the first stages of manufacture.

(*b*) The setting time of the cement, or the amount of gypsum used to regulate such setting.

(*c*) The amount of water used in gauging the pat.

(*d*) Over-trowelling of the pat in preparation for the test.

(*e*) The temperature of the water in which the test is taken.

(*f*) Disturbance of the water into which the pat is placed, and the amount of alkaline matter in such water.

Of these many causes of failure it may be said that only the first has any bearing upon the actual value of the cement as a commercial and engineering commodity. Even as an index of over-liming or under-burning the cold plunge test is not reliable, as it has often been noticed that cement which has been passed as thoroughly sound in this test was not merely unsound, but completely disintegrated, when subjected to the boiling test.

Davis suggests, therefore, that the cold plunge test is in no way to be relied upon as determining the qualities of cements, since many quick-setting cements under certain circumstances obtain a mechanical strength immediately after gauging, and therefore pass the test, whilst a slow-

setting cement, which may be of a much higher quality, does not gain this mechanical strength, and, consequently, often shows signs of disintegration in the cold plunge test.

Delivery of Cement.

Packages.—*B.S.S. No. 12*, 1931, Clause 16, states :—

> "Cement shall be delivered in bags, wooden casks or steel drums bearing the Manufacturer's name or recognised mark. A Purchaser desiring to have the cement delivered in bags, wooden casks or steel drums sealed or of any particular size must so specify at the time of ordering."

Though barrels are used in special cases, the bulk of the cement used in this country is despatched from the works either in jute or paper bags. Paper sacks have many advantages over jute sacks, and since their introduction for holding cement a few years ago they have gradually replaced jute sacks, until now about three-quarters of the output of cement in this country is sent in paper bags. The price of the container is 4s. per ton of cement (20 bags) or 2½d. each bag for quantities less than a ton.

Advantages of Paper Sacks.—The advantages obtained by using paper sacks are summed up briefly in the following :—

1. Neater and cleaner packages to handle.
2. Large quantities can be handled by a chute with greater speed than when the jute sack is used.
3. Can be emptied completely of all cement as there are no interstices to hold the cement.
4. No time wasted in opening as with jute sacks, the paper simply being ripped open with a knife.
5. Paper sacks entirely eliminate all trouble and expense of recording for return to Works for credit. Also no trouble or cost in collecting, carting and tracing empties, etc.
6. Cement more perfectly stored because of the greater damp-resisting qualities of paper as compared with the open texture of jute.
7. Better protection against rain.

Money tied up with Jute Sacks.—Whilst admitting the

numerous advantages which paper sacks have over jute sacks, there is one point which is often not appreciated fully by a builder. Suppose he wants 100 tons of cement on the job in 1-cwt. sacks. If he gets the supply in jute sacks, he will have to pay (except in a few areas) a price for bag hire, which, at 1s. 7½d. per bag, will be 32s. 6d. per ton, or £162 10s. for the consignment. As 1s. 6d. is allowed per bag when returned, he will, of course, get back £150. But, for a definite period, this money is locked up when it could be doing useful work elsewhere. Now, if paper sacks are used, the total outlay for sacks for 100 tons of cement is £20, the whole of this being non-returnable. This is surely a better financial proposition.

New Type of Paper Sack.—In "*Cement, Lime and Gravel,*" April, 1930, reference is made to a new type of paper sack recently introduced in Europe under the trade name "*Jar,*" having the peculiarity of being constructed of a single sheet of paper rolled so as to form several thicknesses or layers. One of the layers (the second in the case of four or the third in the case of five or six) is rendered impermeable by means of a preparation appropriate for the material to be bagged, this preparation having an oil base for cements, limes and plasters, and a paraffin base for certain other materials. The impregnating of an interior layer avoids contact of the impermeable material with the material to be sacked, and at the same time avoids damage by scratches on the outer layer. Only the bottom of the sack is sewn, and the bags are filled by special machines, as in the case of the valve bags.

Aeration of Cement.

Years ago, cements which were imperfectly burned and coarsely ground were liable to expand after the concrete had been placed in position, but this trouble need not now be feared. A modern cement is ready to use as soon as it reaches the job, and any attempt at aeration can result only in a loss of strength. There need be no fear of expansion if the cement has passed the *B.S.S.* test for expansion.

Consider what would happen if a batch of present-day cement were to be spread out in a thin layer and exposed to the atmosphere for, say, six months. It has a great affinity for moisture, and it is certain that, at the end of this period, so much moisture would have been absorbed that the cement would have become useless. If it had been exposed for only six days instead of six months, the deterioration would have been correspondingly less.

It is clear, then, that from the point of view of expansion, aeration is not necessary, and is actually harmful to the strength.

Another reason which is sometimes given for aeration is that a quick-setting cement is rendered slow-setting. If the intention is to get a slow-setting cement it should be obtained from the makers. It cannot be denied that aeration does modify the setting time of a cement—but not always in the way intended. Cement has a strong affinity for moisture and for carbon dioxide. Both of these are in the atmosphere in varying proportions according to time and locality. The absorption of moisture results in a retardation of the setting time, whilst the absorption of carbon dioxide results in an acceleration.

Tests reported several years ago at the *Concrete Institute* (Vol. 5 of the *Proceedings*) showed that there was no relation between the effects of aerating cement for 24 hours and storing in sacks for two weeks or a month ; further, that the setting time is differently affected when the same cement is aerated or stored in bulk in different localities or at different periods. In some cases the effect of 24 hours' aeration is the opposite to that produced by storage, and storage or aeration at one period may have an opposite effect to storage or aeration at another period. This appears to dispose effectively of the somewhat prevalent idea that changes in setting time are due to some inherent property of different cements. The retardation or acceleration of setting time on storage or aeration cannot be due to peculiarities in the cements themselves, but must be due to chemical changes brought about by the absorption of some constituent present in the atmosphere.

In brief, aeration was used to alter the setting period

of the cement or to avoid possible future expansion; but there is now no justification for its use, since a cement passing the *B.S.S.* will not "blow" later, and the setting time can be controlled to some extent by the makers to suit an individual's requirements.

Hot Cement.

A "hot" cement may mean one of three things:—

1. A cement which is hot to the touch.
2. An unsound cement, which causes the set concrete to crack.
3. A quick-setting cement.

Confusion is often caused during conversation because one man means one thing by "hot cement" and another man means something quite different, and the term requires further explanation. There is no definite connection between these three meanings, though it was thought at one time that a cement hot from the mill was necessarily unsound. Cement which is hot to the touch is not for that reason unsatisfactory. During grinding the cement becomes heated, and its temperature may be as high as 150° F. when taken to the silo for storage. Generally, the finer the grinding, the higher will be the temperature of the cement as it leaves the mills. A large silo of hot cement has little chance to cool, and, therefore, it is quite likely that when the cement is packed it will still have a fairly high temperature—say 100-120° F. Hence it reaches the consumer in a hot condition. This applies more particularly to rapid-hardening cement and cement in paper bags. Even if the cement had a temperature of 120° F. when used it would raise the temperature of a 4 : 2 : 1 mix only about 2° F. Bags of hot cement stacked in single tiers will become of normal temperature in 1-2 days.

It has been suggested that the application of the word "hot" to a quick-setting cement may have originated from the fact that quick-setting cements show a marked rise in temperature during setting. This is not a disadvantage, though at one time it was considered as such.

The cement will be quite sound, the heat being caused by the great chemical activity.

In *Bulletin No. 7* of the *Building Research Station* there appears definite authoritative information on the question of "Hot Cement." The tests carried out are described in this publication and also in the *Report* of the *Building Research Board* for 1929. Setting-time tests showed that the "hot cement" set more quickly than the cooled cement, the effect being more marked in the case of the initial setting time. There was, however, a difference of only one half-hour in the final setting time between cement which was at 122° C. at the time of mixing and that which was at only 15° C. This difference may be considered of little importance. (The writer has noticed that some "hot" cements set more quickly when cooled.) With regard to the tensile strength of 1 : 3 standard sand-mortar briquettes, stored in water for 2, 6 and 27 days after 1 day in moist air, the results showed that the strengths of such briquettes prepared with cement which was at 122° C. before adding the sand and water were lower than those obtained with cement at 15° C. The reduction in strength varied from 21 per cent. at 3 days old to 16·5 per cent. at 28 days old. In all cases, however, the cement passed the British Standard Specification. Crushing-strength tests on concrete prepared from cement of various temperatures showed that, in a mix such as 1 : 2 : 4, where the cement content is relatively small, there was no apparent effect on the strength, this probably being due to the rapid dissipation of the heat to the aggregate and water. In general, it was concluded from the tests carried out, that the effects of using "hot" cement under conditions likely to be found on a job are unimportant.

Weight of Cement.

Weight per Cubic Foot.—It has been shown that the weight of a cubic foot of cement depends on—

1. Shape of container. Using the same filling procedure, a shallow, broad container gives a lower result than is obtained with a tall, narrow vessel of the same capacity.

2. Capacity of container. It was reported in *Building Science Abstract No. 1029*, June, 1928, that when a 10-litre container is used, the weight per litre is found to be higher than that obtained with a 1-litre vessel, and lower than that given by a 100-litre measure.

3. Method of filling.

4. Fineness of grinding of cement.

The first three factors can be standardised, but the last will depend on the cement.

The value of 90 lbs. per cubic foot is the one usually taken for dealing with ordinary cement. If we assume that this weight corresponds to a residue of 10 per cent. on the 170-mesh sieve (*B.S.S.* maximum), the following values will be approximately correct :—

Residue on 170-mesh Sieve.	Weight per Cubic Foot.	Cubic Feet per Ton.
10 per cent.	90 lbs.	24·9
6 ,,	87 ,,	25·75
3 ,,	84 ,,	26·7
1 ,,	81 ,,	27·6

This, of course, is only a comparative table. It is interesting to note, however, that in the B.S. Specification for concrete kerbs it is suggested that the weight of rapid-hardening cement may be assumed as 80 lbs. per cubic foot. This figure corresponds to a residue of less than 1 per cent. In one particular set of tests, carried out by an independent expert, the following values were obtained :

Cement A—77 lbs. per cu. ft. or 29 cu. ft. per ton.

Cement B (R.H.)—70 lbs. per cu. ft. or 32 cu. ft. per ton.

This indicates the importance of choosing a cement with care.

A few people still talk about " bushels " of cement. A bushel is approximately $1\frac{1}{4}$ cu. ft., so that, using a weight of 90 lbs. per cu. ft. a bushel may be taken as 1 cwt.

Specific Gravity.—It is no longer necessary to insist on

a certain specific gravity for cement, since it is no guide to proper calcination. Actually it depends on the age of the cement and the conditions of storage. A finely-ground cement, under bad storage conditions, would rapidly absorb both moisture and carbon dioxide, and this would lower the specific gravity of the cement. It is sometimes suggested that measurement of the specific gravity be made after the cement has been heated at 100° C. This is without point, as neither the carbon dioxide nor the absorbed moisture (which is chemically combined) would be driven off at this temperature.

"Balling" of Cement.

The following details, given by Dr. Killig in "*Zement*," are reproduced from "*Concrete and Constructional Engineering*," vol. 16, No. 7 :—

"The formation of 'balls' when Portland cement sets is due to a disturbance of the homogeneity of the cement by the addition of water, and is a result of the presence of impurities which act as nuclei and facilitate the formation of new crystals. These impurities need not have any direct chemical action on the cement, as have calcium chloride, soda, etc. ; it is sufficient if they withdraw water mechanically from the paste and so increase the rate of setting. Consequently, 'balling' may be produced by sawdust, pieces of bread, flour, paper, cloth and other fibrous materials. Sometimes the impurity expands and so causes the balls to crack.

"All cements do not 'ball' with equal facility ; some appear to have a composition—not definitely known—which increases the 'balling' tendency, whilst with others the presence of too much gypsum increases the defect. Cements which do not set in less than 3-4 hours do not 'ball' on the addition of glue, sawdust, etc., but do so readily if calcium chloride or soda is added.

"Portland cement sometimes 'balls' when stored ready for use, if the roof or sides of the bin or shed are not water-tight. For instance, in one store a leak developed in the

roof and admitted rain ; some days later when the cement was taken out of the store it contained a number of balls. When these balls had been kept for some months they were found to have a radial structure and to be distinctly crystalline—a condition quite different from that of cement mixed with water and allowed to harden in the usual manner."

Colour of Cement.

There is a prevalent idea that the strength and activity of cement can be judged from the colour. This is quite erroneous, as has been pointed out on various occasions. The hydraulic and siliceous contents of cement clinker have only a negligible influence on the colour of the cement. The factors which affect the colour may be :

1. Chemical.
   (*a*) Iron content.
   (*b*) Degree of oxidation.
   (*c*) Degree of burning.
2. Physical.
   (*a*) Size of particles.
   (*b*) Presence of foreign matter in the raw mix.
   (*c*) Addition of foreign matter during crushing.

Of all these the only one which can definitely be associated with a reduction in strength is inadequate burning. A cement which is underburnt may be light grey, light brown or yellow. Here the light colour does indicate inferior material. Iron in cement is derived from the raw materials used, and the cement may contain any proportion of iron oxide up to 5 per cent. With 0·5 per cent. or less the cement will be white, but as the quantity increases from 0·5 to 5 per cent. the colour changes from white to light grey, and then to dark grey with a tinge of brown. Iron oxide has no influence on the quality. Coarse particles of cement have a darker colour than the general body of the material, because cement clinker is almost black, and pieces which are not very finely ground retain this appearance.

The term "foxy" is sometimes applied to a Portland cement having a brownish tinge, and this, according to D. B. Butler, denotes insufficient calcination, or the use of unsuitable clay or possibly excess clay. Butler further mentions that if a Portland cement contains a large quantity of unburnt particles they tend to rise to the surface on trowelling on account of their lower specific gravity, thus forming a yellowish-brown film. This film is noticeable at the broken section of a briquette.

It can be stated quite definitely, therefore, that the colour of a cement should not be used as a guide to quality. Inferior quality due to underburning would be revealed by the usual tests for soundness, strength and chemical composition. A change in colour does not necessarily mean a change in quality.

The following useful information regarding the colour of Portland cement is given in the Report of Committee 202, "Variations in Standard Portland Cements," *Journ. Am. Conc. Inst.*, Nov., 1929 :—

"Portland cement is generally referred to as being grey in colour. This is essentially true, although certain cements are at times of a distinctly yellowish tint and might be said to have a tan colour ; others have enough of a red tinge to partake of a muddy brown colour. In any case these colours are due to two or three of the minor oxides present in the raw materials : titanium oxide to a lesser degree and iron and manganese oxides to a greater extent. The pure compounds of lime, silica and alumina, which comprise 90 per cent. or more of cement, are white. Although all three of the first-mentioned oxides are seldom present in total amounts of more than five per cent., they produce the colour in the cement. This colour, however, is modified by the oxidising or reducing atmosphere of the kilns, the temperature during burning, and certain unknown conditions during cooling. Generally, the higher the iron oxide content and the more reducing the flame the darker grey the colour. Low burning with high iron oxide content gives the tan shades, and with low iron oxide the light grey shades. The muddy brown cement is the result of the presence of manganese, which in some cements may

approach a maximum of one per cent. when calculated as the dioxide.

"It requires rather a colour-sensitive eye to note the differences in colour produced in concrete by the use of widely different coloured cements (other than white cement). This is particularly true of the tan or grey cements; the brown cements are inclined to yield a concrete rather readily distinguishable by its more brownish shade. But in few cases is the difference in colour sufficient to be objectionable. Rather, the slight differences are pleasing in breaking up the monotone.

"There is, however, one feature regarding the colour or tint of concrete which should always be seriously considered. This refers to the colour lacking 'life,' whatever that may be. A dead, chalky-appearing result is an excellent indication of poor concrete, and furthermore, more particularly of poorly-made concrete. While it is almost impossible to define a 'live' colour or tint, there is no mistaking such a one when compared with a 'dead' one, and the bringing together of a piece of well-made concrete of almost vitreous texture and a piece of concrete made from an over-watered mix, with its chalky, powdering texture, will leave no doubt in anyone's mind as to the significance of the term. Once having noted this condition it is one that should be borne in mind. The appearance of a chalky, too-sandy fracture in the matrix in concrete, coupled with a lack of 'life' in its colour, be that what it may, is quite positive evidence that too much water has been used in the mix. The appearance of the matrix under such conditions is very similar to that of laitance, and the resemblance extends beyond this physical appearance to the actual conditions under which the materials were produced—namely—the use of too much water."

Storage of Cement.

If cement is to be stored before use it is essential that it should be protected from moisture. This does not mean that the sacks should be thrown indiscriminately on the ground inside an old building, but that real precautions

should be taken. Cement "wants" water sufficiently to draw it from the surrounding air, and, therefore, a storage shed should be as watertight and damp-proof as possible. A concrete floor is the best, laid on a well-drained foundation of cinders or gravel. Even with a floor of this nature it is advisable not to put the sacks directly on the concrete, but to put them on boards which are carried on loose wooden joists resting on the floor. Sacks should not touch the walls of the storage shed.

Cement which has become caked in a bottom sack of a tier may still be quite good, as the caking may only have been caused by the superimposed load. Lumps that are crushed readily between the fingers are satisfactory for use, but lumps which cannot be so broken have probably set by the absorption of moisture and should be rejected.

In *Building Science Abstract No. 242*, February, 1928, it is stated that the changes which occur in cement during storage are (1) due to external agencies, such as the absorption of moisture and carbon dioxide from the air, (2) internal transformations due to (*a*) interaction between the heterogeneous components of the cement, such as hydration of anhydrous lime at the cost of the calcium silicates or aluminates which had hydrated during grinding, etc., (*b*) slow phase transformation of the several components from a metastable to a stable state. The action of external agencies (1) can be inhibited by hermetically sealing the samples.

An examination [11] of the available information reveals a great deal of conflicting evidence with regard to the effect produced by the prolonged storage of cement under various conditions. Some investigators, for example, have found that under certain conditions the setting time of the cement has been increased, while others have found the reverse. It is with a view to clearing up some of the uncertain points, especially as regards the effect of storage conditions upon the setting time, fineness and strength of the cement, that work has been started by the *Building Research Station* on this problem. Reliable information is particularly desirable with regard to the rapid-hardening cements recently placed on the market.

Arrangement of Store.—It is seldom [12] that proper precautions are taken to ensure that the cement is used as soon as possible after it is delivered; often the bags are put simply in front or on top of others in a shed, with the result that the last deliveries are used first and the remainder of a previous consignment may not be used for months.

A good method of avoiding this trouble is to lay out the cement store as follows. The shed to be wide enough to take one row of bags on each side (piled up four or five high), with ample space along the middle so that men have plenty of room to hoist the bags and to turn a truck. A further advantage of ample free space along the middle of the shed is that the bags if necessary may be stacked in two rows along each side, thus doubling the amount of cement that may be stored in the shed. For preference there should be a door at each end, so that the bags may be taken in at one end and out at the other.

Change of Setting Period.—It has been found that when some cements are kept in storage they "quicken-up," that is to say, they change from normal-setting to quick-setting cements. When this occurs nodules are usually formed when the cement is gauged with water. The reason for this quickening-up is not quite clear, but it is thought that the tendency is only present when the gypsum content of the cement approaches a certain amount.

A normal-setting cement frequently changes to a "flash-setting" cement when the bag is left exposed for any considerable time to the hot sun. In *Building Science Abstract No. 247*, Feb., 1928, it is stated that there appears to be a relationship between this tendency to "flash-setting" and the calcium aluminate content.

Storage for Long Periods.—It should not be necessary to store cement for long periods in this country, but if circumstances are such that this is found necessary, the best method to adopt is to empty the bags into specially prepared airtight and damp-proof bins to a depth of five or six feet. The top two inches or so will form a crust which will have to be discarded, when the cement is used, but the rest will be quite fit for use even after one or two years. If a large consignment of cement has been obtained and it is found

impossible to use it for some time, the writer would suggest that negotiations should be opened with the suppliers to see if they will not take it back. This would be the cheapest course to adopt in almost every instance.

If kept in bags for long periods, the bags should be covered with straw, canvas, tarpaulin or similar material to reduce air circulation. The cement should not be disturbed, as moving the bags about "exposes" fresh cement to the air.

Deterioration.—The strength of cement is reduced by storage. So many factors, however, are unknown variables, that it is impossible to foretell quite what deterioration to expect. For ordinary conditions, however, the following reductions may be expected at 28 days :—

After storage	for	3 months,	20	per cent.	minimum.
,,	,,	6 ,,	30	,,	,,
,,	,,	1 year, .	40	,,	,,
,,	,,	2 years, .	50	,,	,,

The question is further complicated by the fact that the reduction of strength reduces with the age of the specimen.

Storage Period.	Age at Test.	Reduction.	Mix.
3 months	7 days	27 per cent.	5 : 1
,,	28 ,,	25 ,,	5 : 1
,,	6 months	16 ,,	5 : 1

Safety Rules.—Cement should not be piled [13] more than 10 bags high, except in a store built for the purpose.

The first four end bags should be cross-piled in two separate tiers up to the fifth bag, where a step-back of one bag in every five should be made. Beginning with the fifth bag, only one cross tier is necessary.

The back tier, when not resting against a wall of sufficient strength to withstand the pressure, should be stepped back with one bag in every five, the same as the end tiers.

Cement in outer tiers in all cases should be piled with the mouths of bags facing the centre of the pile.

When cement is removed from the pile, the length of the pile should be kept at an even height and necessary step-backs every five bags must be left.

Cement delivered in paper bags should be handled with precautionary measures to prevent the bags from breaking and showering the workmen with dry cement.

Men handling cement should wear goggles and tight neck and arm bands.

A cream should be provided and used on the hands, face and other exposed parts to prevent cement burns.

A bucket containing dilute acid, such as acetic acid (vinegar), to neutralise the alkali of cement, should be kept handy for use should workmen feel cement burning them.

CHAPTER II.

OTHER CEMENTS.

RAPID-HARDENING PORTLAND CEMENT.

The Need for a Rapid-Hardening Cement.—The need for a consistently reliable rapid-hardening cement was very marked a few years ago, with the result that "*Ferrocrete*" was produced and marketed. Since this, numerous other rapid-hardening Portland cements have been put on the market, but as they are all of the same type it will be necessary only to refer to the results obtained with "*Ferrocrete.*"

Specification.—At the present time there is no standard specification for rapid-hardening Portland cement, but indications point to the fact that there will probably be one issued either by the *B.S.I.* or by one of the Engineering Institutions. In the meantime, reference may be made to *B.S. Specification No. 340, 1928*, for "Concrete Kerbs, Channels and Quadrants in Portland Cement."

Part of Clause 1.

"The use of rapid-hardening cement shall be permitted provided that it complies in all respects with the foregoing Specifications, and in the case of neat cement and cement and sand attaining the breaking strengths required by these Specifications in periods not exceeding 2 days and 8 days, respectively, in place of 7 days and 28 days, the volume of cement required by Clause 3 shall be calculated on a density of 80 lbs. per cubic foot, and the period of maturity as defined by Clause 19 shall be 14 days."

Clause 19.

"No Kerbs, Channels or Quadrants which were manu-

is important, since it offsets, to a large extent, the extra price for rapid-hardening Portland cement, which is in the neighbourhood of 7/6 per ton.

Strength.—The following table gives the results of tests on a high-class rapid-hardening cement, and may be used as a guide for strengths of mortar and concrete.

Age.	Sand Tensile 3 : 1, lbs./sq. in.	Sand Compression 3 : 1, lbs./sq. in.	Crushing Strength, lbs./sq. in. (6″ Cubes), 4 Parts Ballast, 2 Parts Sand, 1 Part "*Ferrocrete.*"
1 day.	600	5,000	3,000
2 days.	690	6,600	4,300
7 days.	860	9,400	6,500
28 days.	890	10,500	7,700

For a 4 : 2 : 1 concrete the usually accepted figure for the working stress is 600 lbs. per square inch, but a slight concession has been granted in certain quarters when a rapid-hardening Portland cement is used. For instance, the Ministry of Transport will allow this working stress to be raised by 25 per cent., *i.e.*, to 750 lbs. per square inch. This is a move in the right direction, but is not enough. Many firms of repute would be only too glad of the opportunity to design and construct guaranteed reinforced concrete works with working stresses 50 per cent. higher than those now allowed.

Not only does a raising of the working stress show an economy in cement, but there is an appreciable saving in aggregates, and this results in a reduction of the total dead load of the building without any reduction in the factor of safety. Apart from the saving thus caused, this consideration is important where ground of poor bearing capacity is encountered. A minor advantage is a saving of head room by the reduction in size of beams and slabs, and a consequent greater cubic content of the building.

The following table shows results obtained in compression

tests of 4 : 2 : 1 concrete cubes made on the job with granite, sand and cement by a Lancashire firm of contractors.

Compression Tests, lbs./square inch.		
7 Days.	28 Days.	90 Days.
5,220	6,000	7,220
4,540	5,328	7,280
6,440	7,180	9,330
5,040	5,780	6,930
5,190	6,820	8,400
5,880	6,440	7,710
Av. 5,385	6,258	7,812

Setting and Hardening.—As mentioned previously, it is necessary to distinguish between quick-setting and rapid-hardening. For instance, " *Ferrocrete* " is not quick-setting, having a setting period comparable with that of ordinary Portland cement. Therefore it allows ample time for mixing and placing the concrete in position before the set takes place. The chief value of a rapid-hardening cement is, as its name implies, its high early strength, and in general it might be said that concrete made with rapid-hardening Portland cement attains a strength at 4 days equal to that attained by concrete made with normal Portland cement in 4 weeks. The value of a rapid-hardening cement is particularly noticeable during the winter, when the hardening of concrete is retarded by the low temperatures. When used, the risk of damage by frost is considerably decreased, because the period required to reach the necessary degree of hardness to resist the attack of frost is much less than that for normal Portland cement.

The heat generated by cement on setting has already been mentioned, and reference to Fig. 1 will show that

it is particularly noticeable in the case of a rapid-hardening Portland cement. It is now generally accepted that the amount of heat generated by cements during the setting and hardening period is about the same, but that the dissipation of this heat is spread over the whole period of hardening. Thus the shorter the hardening period the greater the rise in temperature. In one case during winter construction work in 1928, a floor slab 2 feet thick, made with "*Ferrocrete*," was placed just before a spell of frost lasting for 10 days. During the whole of this period the ground around the slab was frozen hard, but there was no sign of freezing on the slab, which was, in fact, covered with shallow pools of water.

Saving in Formwork.—The advantages of a rapid-hardening Portland cement are obvious, and for practically all purposes more than compensate for the small extra cost. The saving in formwork is very marked, as will be seen from the following periods after pouring at which forms may be stripped :

Column, beam or girder sides may be stripped in 24 hours.
Undersides of floor slabs ,, ,, ,, 48 ,,
Undersides of beams and girders may be stripped in 3 to 6 days.

A saving of one-third of shuttering costs may easily be effected when "*Ferrocrete*" is used, and the earlier date at which a building may be used may represent considerable sums.

With the use of rapid-hardening Portland cement, wet mix precast concrete units may be removed from moulds 24 hours after casting, and used in building construction four days later. Piles may be stripped of their moulds in 24 hours, and driven in five to seven days.

Roads.—The all-concrete road made with "*Ferrocrete*" can be opened to heavy traffic within a few days of laying, under favourable conditions, whereas in the case of ordinary Portland cements it is necessary for such a road to mature for a month before traffic is allowed over it.

Apart from the great convenience to the community, this saving of time means a corresponding reduction in the

initial cost of the road, since it brings down the cost of watching, covering, maturing and lighting to a minimum.

Increased Cost of the Concrete.—To make 1 cubic yard of 4 : 2 : 1 concrete, the following amounts of the constituent materials will be required :—

0·88	cubic yard	of	broken stone.
0·44	,,	,,	sand.
0·22	,,	,,	cement.

When comparing two concretes, one made with ordinary Portland cement just satisfying the B.S. Specification, and the other with a rapid-hardening cement, the volumes of cement used may be changed into corresponding weights by taking 90 lbs. per cubic foot for the normal cement, and 80 lbs. per cubic foot for the rapid-hardening cement.

Taking the weight of the cement at 90 lbs. per cubic foot, 0·22 cubic yard will weigh 535 lbs. If the price is assumed as 50/- per ton, the cost of the cement required to make 1 cubic yard of finished concrete is 11·9 shillings.

If no allowance be made for the lighter weight, and a price of 57/6 per ton be assumed, the cost of the rapid-hardening cement in one cubic yard of finished concrete is found to be 13·7 shillings. If, however, the fine grinding is taken into account, the cost will only be 12·2 shillings.

Thus the increased cost of the concrete when rapid-hardening cement is used will vary from 0·3 shilling to 1·8 shillings per cubic yard of concrete, or say from ½d. to 3½d per square yard for a 6-inch road slab. This increase usually is more than balanced by the savings resulting from the use of rapid-hardening cement, such as reduced watching and lighting costs, increased strength, reduced traffic delays, etc.

Aluminous Cement.

Description.—Aluminous cement was first made in France in 1908, and it has been the subject of prolonged tests for endurance, especially in sea water and sulphate waters.

These tests have shown aluminous cement to be a stable product, and there need be no fear of its failure in course of time. It contains the same constituents as Portland cement, but in different proportions. See "Composition of Cement," Chapter I. Aluminous cement is made by melting together bauxite and lime (bauxite is a mineral composed principally of alumina). The cement is a very dark, almost black, powder, and gives a darker concrete than Portland cement.

Cost of Manufacture.—Aluminous cements are costly to manufacture for the following reasons:—(1) There is no suitable bauxite existing in England and, consequently, the material has to be imported. (2) The fused material is much harder than Portland cement clinker, and therefore takes longer to grind.

Fusion.—P. H. Bates [15] states that the amounts in which the oxides of the several elements are present result in a low-melting mixture, which does not clinker easily, but passes from a powdered stage to a fused condition within a very narrow range of temperature. Thus the alumina cements are fused because they cannot be clinkered economically, and not because high temperatures are of necessity required to bring about the desired combination of the elements. The fusion temperature is in fact about 100° C. lower than that at which Portland cement is clinkered. The latter is clinkered and not fused because the fusing temperature is more than 200° C. higher than the clinkering temperature. Such higher temperatures are not attainable in kilns of the type now used, and furthermore it has not been shown that Portland cement is improved by heating above the clinkering temperature. Portland cements are rich in silica and very low in alumina and iron oxide as compared with the high-alumina cements, and are essentially a mixture of two silicates of lime ($3\ CaO.SiO_2$, and $2\ CaO.SiO_2$).

Brands.—Two brands of aluminous cement are sold in England, namely, "*Ciment Fondu*," sold by The Lafarge Aluminous Cement Co., Ltd., and "*Lightning*," sold by The Cement Marketing Co., Ltd. These cements are referred to variously as "Aluminous Cement," "High

Alumina Cement," "Fused Cement," and sometimes "Electric Cement." "*Lumnite*," to which reference is often made in technical literature, is an American aluminous cement made by The Atlas Lumnite Cement Co., 25 Broadway, New York. "*Ciment Fondu*" was put on the market as a commercial article in 1918. "*Lightning*" has been made since 1924.

Characteristics.—By using aluminous cement greater strength at 1 day can be obtained than with ordinary Portland cement at 100 days under the same conditions. Concrete piles made with aluminous cement can be driven two or three days after moulding. Aluminous cement is unaffected by frost. Shuttering for vertical walls can be removed after 6 hours and used twice per day. Aluminous cement is proof against sea water or waters containing sulphates or magnesium salts. The crushing strength at 24 hours on 6-inch cubes, 4 : 2 : 1 mixture (laboratory specimen), is 8,000 lbs. per square inch.

The following laboratory tests show the comparative values of aluminous cement, rapid-hardening and ordinary Portland cements.

Compression Tests on 6-inch Concrete Cubes composed of 1 Part Cement, 2 Parts Sand, and 4 Parts Ballast, in lbs. sq. inch.

Cement.	8 Hours.	24 Hours.	2 Days.	3 Days.	5 Days.	7 Days.
Aluminous cement, .	1,800	8,000	...	...	...	8,800
Rapid-hardening Portland cement, . .	...	3,000	4,300	5,000	6,000	6,500
Ordinary Portland cement, . . .	...	...	...	...	...	4,500

Aluminous cement is slow setting, having generally not less than 1 hour initial set, thus allowing ample time for mixing and placing the concrete.

"*Lightning*" and "*Ciment Fondu*" comply with the "Chatelier test," comprised in the B.S. Specification for Portland cement.

Instructions for Use.—Aluminous cement is used and mixed in exactly the same way as Portland cement, but :—

1. The concrete work must be kept wet. A. F. R. Lund, in "*Zement*," states [16] that the form of deterioration of aluminous cement concrete surfaces known as "dusting down," is due to the sensitivity of aluminous cement, during the setting process, to changes of water content, and is of the opinion that a loss of 11 per cent. water will suffice to cause surface disintegration, whereas Portland cement may be expected to be unaffected by the loss of 38 per cent. of the mixing water.

2. Concrete made with aluminous cement should be mixed well and not made too dry. More water should be used than with Portland cement, but sloppiness should be avoided.

3. All forms should be thoroughly wet before filling with concrete, to prevent loss by absorption, but do not leave water standing in the moulds.

4. For roadwork, trenches, etc., water the ground and surrounding work freely before placing the concrete.

5. Do not use neat or abnormally rich mixtures.

6. Do not mix aluminous cement with Portland cement or lime even in the very smallest quantities. All shovels, concrete mixers, mixing boards, barrows, etc. should be well cleaned before use with aluminous cement.

7. The same care as to the quality and grading of the aggregate is necessary as with Portland cement concrete.

8. If it is required to bond aluminous cement concrete to Portland cement concrete which has set, the surface of the old concrete should be roughened, cleaned and thoroughly wetted—then, before placing the aluminous cement concrete, a rich creamy grout should be applied to the old surface.

9. If it is required to bond to new aluminous concrete which has hardened, brush the surface vigorously with soda and water.

Specification.—In *The Structural Engineer* for October, 1930, there is a tentative specification for high-alumina cements. The tests recommended are for

1. Fineness.
2. Chemical composition.
3. Compressive strength.
4. Setting time.
5. Soundness.

It appears that, as far as possible, the specification has been drawn up parallel to the B.S. Specification for Portland cement. The following summary has been made from this tentative specification.

Storage.—Aluminous cement should be stored in a perfectly dry, watertight shed, the floor of which should be raised above the ground, as the qualities of this cement are seriously affected by moisture.

Tests.—Tests shall be carried out without previous aeration of the sample. Should the purchaser desire to carry out tests to satisfy himself that the cement as delivered is in good condition, the tensile strength test may be made. The result of such test by itself, however, shall not constitute a valid reason for the rejection of any cement.

Fineness.—The residue on the 180-mesh sieve shall not exceed 14 per cent. The residue on the 76-mesh sieve shall not exceed 1 per cent.

Chemical Composition.—The total alumina content shall not be less than 32 per cent. of the whole. The ratio of the percentage of alumina to the percentage of lime shall be not less than 0·85 nor more than 1·3.

Compressive Strength.—The compressive strengths of 3-inch cubes (3 : 1 mix, by weight) shall be :—

Age.	Compressive Stress, lbs./sq.inch.
24 hours.	5,000
3 days.	6,000
7 days.	No decrease.
28 days (if tested).	No decrease.

Setting Time.—The initial set shall take place in not less

than 30 minutes nor more than 4 hours. The final set shall occur not more than 2 hours after the initial set.

Soundness.—The cement shall be tested for soundness by the "Chatelier method," and shall not show an expansion greater than 1 mm.

Tensile Strength.—This test is for acceptance purposes only. The tensile strengths of briquettes (3 : 1 mix, by weight) shall be :—

Age.	Tensile Stress, lbs./sq. inch.
24 hours.	450
7 days.	525, or not less than at 24 hours.

Heat on Setting.—The rate of hardening of aluminous cement is so rapid that a considerable amount of heat is generated during the process, and the water in the concrete is liable to be evaporated. Therefore, in order to replace the water lost by evaporation, the concrete must be kept continuously wet from the time it commences to harden for 24 hours.

With an appreciable thickness of 4 : 2 : 1 concrete the rise in temperature may amount to 25° to 30° F., so that, even if the wet concrete be placed in 15 degrees of frost, the temperature of the concrete itself will remain above freezing point. The hardening process may be delayed, but the concrete will be uninjured.

The following conclusions,[17] based on some American tests, are of interest :—

1. When the specimens are made of neat alumina cement of average consistency, and are confined so that the heat generated cannot escape, a temperature above the boiling point of water may be expected, due to the chemical action of setting and hardening.

2. A decrease in the richness of the mix reduces the temperature-rise.

3. An alumina cement specimen reached a temperature four times that of a similar Portland cement specimen.

4. The rise in temperature with alumina cement takes place very suddenly. In every instance a rise of over 100° F. took place in approximately 15 minutes.

5. A high initial temperature causes quick setting of an alumina cement mix.

6. In all cases, for the same mix and the same water-cement ratio, the specimens composed of alumina cement generated over twice as much heat as similar specimens of Portland cement.

7. At initial temperatures below 80° F. the temperature of a concrete using alumina cement will start to rise after about 5 hours.

Comparison of Setting Periods.—Below is given [18] a summary of the setting properties of "*Lumnite*," and a corresponding list for Portland cement.

Condition or Reagent.	"*Lumnite.*"	Portland Cement.
Temperature.	An increase of temperature between 35° and 90° F. slows set.	Increase of temperature hastens set.
Humidity.	Does not greatly affect set.	Affects set considerably.
Hydration previous to gauging.	Increase of hydration greatly affects set.	Increase of hydration slows set.
Percentage of water used in gauging.	Increase of water slightly slows set.	Increase of water greatly slows set.
Fineness.	Increase of fineness hastens set.	Increase of fineness hastens set.
Bases.	Greatly hasten set.	Generally hasten set.
Acids.	Hasten set.	Effect variable.
Sulphates.	Greatly hasten set.	Generally hasten set.
Chlorides.	Retard set.	Generally hasten set.
Nitrates.	Retard set.	..
Moist carbon dioxide.	No effect.	Greatly hastens set.

Storage.—Aluminous cement, like Portland cement, depends for its setting and hardening properties on its chemical action when placed in contact with water, and

must, therefore, be kept free from moisture, if deterioration is not to take place. Even though transported and stored in paper bags, which are highly resistant to the penetration of moisture, it nevertheless will absorb moisture whenever possible. The storage of aluminous cement should be given the same careful consideration as that of Portland cement.

White Portland Cement.

"White cement" may, or may not, be a Portland cement. There are at least three "white cements" (which have been and are being used in this country) which are true Portland cements, namely, "*Atlas*," "*Medusa*" and "*Snowcrete*." The first two are imported from U.S.A., whereas "*Snowcrete*" is a British product. "*Snowcrete*" was put on the market in 1929, and has already become firmly established. Other "white cements" usually are either hydraulic limes or gypsum plasters. A "white cement" of the first type would be considered expensive if sold under its right name. A cement of the second type consists essentially of calcium sulphate, and is, therefore, of no value for outside work.

It is difficult to refer to prices of materials in a book of this nature, as they are apt to vary considerably from time to time according to supply, demand, manufacturing processes, etc. But as a rough guide the following may be used :—

Normal Portland cement, .	£2 10s. 0d. per ton.
"*Snowcrete*," . . .	£9 10s. 0d. per ton.
"*Atlas*" and "*Medusa*," .	£14 0s. 0d. per ton.

Cement prices can always be obtained from the trade journals. The standard packing of "*Snowcrete*" is in 1 cwt. paper bags.

Cost of White Cement.—White Portland cement is expensive for the following reasons :—(1) The proportion of iron oxide (which material gives the grey colour to ordinary Portland cement) should be less than 1 per cent., which

means that special raw materials have to be used, such as china clay and a pure limestone. In this country it is impossible to find in one locality the necessary raw materials free from iron, so that they have to be transported from suitable sites to the works. (2) During all stages of manufacture the materials used and the finished products must not come in contact with iron. This means special cleanliness, and great care to avoid abrasion of the steel and iron plant in the various parts of the works. (3) Calcination must be effected by means of a special fuel (coal or oil) and only selected firebrick may be employed. (4) There is a comparatively small demand, and this usually implies higher costs.

Though at first sight the cost would appear prohibitive, it is not really so, as the cement need only be used for the surface coating of most work and not throughout the mass of the concrete. Thus, the relatively small quantity required, and the fact that the product is exceedingly strong and durable, often enable this cement to be used without financial considerations becoming of a serious nature.

Aggregate for White Cement.—For the successful use of white cement, special attention should be paid to the aggregate. In addition to the usual requirements it is necessary to have a material which is white or nearly so ; some aggregates which have been found suitable are silica sand, spar, granite, marble, Portland stone and crushed flints.

Failures have been caused by the use of fine silver sands, dusty powdered marble, etc. The nature of coarse granulated sugar is about the standard required for these aggregates (this, of course, applies to use in stucco, etc.).

Coloured Cements.

In spite of the architectural possibilities of ordinary concrete the objection to the traditional surface still carries a great deal of weight. As a result, coloured cements have now been marketed for several years, and there is no doubt

that coloured concrete will play a very important part in future work. It is not necessary to enumerate all the types of structure for which coloured cement is suitable, since it can be used almost everywhere with good effect, so long as the correct colours are used and the work is done carefully.

The question of coloured concrete is dealt with elsewhere, and for the present we are concerned only with coloured cements, by the use of which one type of coloured concrete may be obtained. The colouring of cement is effected either by the addition of suitable powdered admixtures, or by treatment with a special type of vegetable dye. This branch of the subject is dealt with in Chapter VII. When a suitable powdered colour is mixed with cement the result is a coloured cement, and it is quite clear that such a cement may be made either on the job or purchased from the manufacturers. If made on the job particular care must be paid to the type of colour used, and there is always the difficulty of ensuring adequate mixing. The colouring material generally used is ground to such a degree of fineness that it is finer than the cement, and to get this colour mixed thoroughly with the cement means that it should be mixed by machinery. For careful work, therefore, the writer would recommend the use of coloured cement where the colour has been mixed with the cement by machinery, the mixing, if possible, being effected during the grinding of the cement.

Earle's Coloured Cements.—The cost of the coloured cement depends firstly on the cement used as the base, and secondly on the colouring material. For the darker shades ordinary grey cement is satisfactory, but for the lighter tints it is necessary to use a white cement, and this naturally increases the price. As a rough guide a list of colours is reproduced on page 54 by kind permission of G. & T. Earle, Ltd.

"**Colorcrete.**"—A further contribution to the list of coloured cements has recently been made by the Cement Marketing Co., Ltd., who introduced "*Colorcrete,*" a rapid-hardening Portland cement. As already mentioned, it is possible to produce an almost unlimited range of colours in concrete, but many of these, particularly the

more delicate tints, require a base of white Portland cement. There are, however, many types of buildings, etc., in which it is desirable to have coloured concrete, but where the cost of coloured "*Snowcrete*" might be prohibitive. It is for use in such work that "*Colorcrete*" has been introduced. "*Colorcrete*" is at present marketed in two colours—buff and red.

Colour.	Ref. No.	Colour.	Ref. No.
Terra cotta, . .	50 P 5	Light brown, .	65 P 5
	50 P 10	Green, . .	71 P 5
Red, . . .	51 P 5		71 P 10
	51 P 10	Pale green, . .	71 W 5
Dark red, . .	52 P 5		71 W 10
	52 P 10	Yellow stone colour,	80 P 5
Pink, . . .	52 W 2		80 P 10
Brilliant red, .	55 P 5	Cream, . .	80 W 1
	55 P 10	Buff, . . .	80 W 2½
Brick red, . .	50 P 5 (580)	Light yellow, .	80 W 5
Dark brown, .	60 P 5	Yellow, . .	80 W 10
	60 P 10	Violet, . .	95 W 5
Chocolate, . .	61 P 5		95 W 10
	61 P 10	Black, . . .	100 P 5
Burnt sienna, .	63 P 5		100 P 10

"*Colorcrete*" has all the properties of "*Ferrocrete*," and can be used for any class of work for which "*Ferrocrete*" or ordinary Portland cement is employed. The colouring matter in "*Colorcrete*" is intimately mixed with the cement by mechanical means, thus providing a uniformity of colour which cannot be ensured when the pigment is added and mixed by hand. Although local aggregates will give very pleasing colour effects with both buff and red "*Colorcrete*," it is usually better to use specially prepared aggregates. Red granites and sands are to be found in many parts of the country, and can usually be secured at a reasonable price. At the time of writing the cost of "*Colorcrete*" is approximately 20/- per ton more than the cost of normal Portland cement, the actual cost varying according to circumstances.

Aggregates.—Detailed information relating to suitable

aggregates for use with coloured cements, the correct procedure to be followed in various instances, and similar matters, are given elsewhere.

"Super Cement."

"Super cement" is made by a special process as indicated in the following diagram :—

Cement Clinker. Gypsum. Catacoll.

Super Cement Process.

Grinding.

Super Cement.

It will be seen that there is a departure from the ordinary process by the addition of catacoll, a catalytic colloid which, it is claimed, improves the bonding and the waterproofing qualities of the cement.

Cements Made With Blast-Furnace Slag.[19]

These cements were first produced in Germany, and can be divided into two main groups :—(*a*) Mixtures of blast-furnace slag and Portland cement clinker ground together, *e.g.*: the English Portland Blast-Furnace Cement; the German Eisen Portland Zement (Iron Portland Cement). (*b*) Mixtures of blast-furnace slag and lime ground together.

English Portland Blast-Furnace Cement is the subject of a specification issued by the *British Standards Institution, No. 146, 1932.* This permits a cement containing an addition to Portland cement clinker of not more than 65 per cent. of granulated blast-furnace slag. The cement must comply with all the physical tests required for Portland cement.

German Eisen Portland Zement is also a mixture of Port-

land cement clinker and granulated blast-furnace slag, but limited to the proportions of 70 per cent. clinker and 30 per cent. slag. In Germany it is claimed that Iron Portland cement is superior to Portland cement for sea-water work, and large quantities are employed. It may be said that few works of importance or magnitude, if any, have been carried out in this country using cement of this character.

Whereas cements in group (*a*) are made with a proportion of true Portland cement clinker, those in group (*b*) are "slag cements," to which the term "Portland" should not be applied. In this country their manufacture is at present very restricted, and extreme care is necessary if their use be contemplated.

Roman Cement.

Roman cement is not a Portland cement. It is used in cases where a quick-setting cement is essential, but the consumption is rapidly declining. Where quick-setting is of prime importance it is often possible to use a normal Portland cement having quick-setting properties, since this can be purchased at a price much lower than that of light Roman cement. Certain engineers, however, still insist on Roman cement being used. The price is in the neighbourhood of £12 per ton at the Works. It is difficult to give figures which can be regarded as typical, but the following results were obtained on tests made for the writer recently. Usually this cement is used with an equal volume of sand, and this slows down the set slightly.

Setting Time—3-7 mins. initial,
7-15 ,, final.
Soundness—1-3 mm.
Fineness—5-10 per cent. on 180-mesh sieve.
Tensile Strength, 3 : 1, 7 days, 200-260 lbs./sq. in.
,, ,, neat, 7 days, 300-450 ,, ,,

At one time there was a suggestion that a mixture of Roman cement, Portland cement and sand would produce a non-shrinkable mortar, but there is no foundation for this statement. The fact that someone got good results

with such a mixture does not indicate that the mixture itself was responsible, and it should have been the workmanship that should have had the credit for the good results obtained.

The effect of mixing light Roman cement with Portland cement is indicated by the following figures, which are the results of tests carried out for the writer to answer a definite query on this point.

Light Roman.	4 mins. initial set, 5 mins. final set. 7 days neat tensile strength—220 lbs./sq. in.
1 Light Roman : 1 Normal Portland.	14 mins. initial set, 20 mins. final set. 7 days neat tensile strength—260 lbs./sq. in.
Normal Portland cement.	85 mins. initial set, 175 mins. final set. 7 days neat tensile strength—1,070 lbs./sq. in.

It will be seen that the admixture of normal Portland cement with light Roman cement has the effect of increasing the initial setting time, and the 7-days' strength is very little above that of light Roman alone. There does not appear, therefore, to be any advantage in mixing the two cements.

Cost of Cement.

The cost of cement is subject to slight variations, and for the preparation of estimates, etc. reference should be made to current technical literature. The following list, however, gives approximate figures :—

Cement	Approximate Cost per Ton.
British Portland,	£2 10 0
Rapid-hardening Portland,	2 17 6
"*Colorcrete*" Coloured Portland,	3 10 0
British White Portland,	9 10 0
American White Portland,	14 0 0
"Super,"	3 17 6
Aluminous,	5 0 0
Roman,	12 0 0

Consumption of Cement.

The consumption of cement in this country is increasing each year, and the following may be taken as approximate figures for the consumption in Great Britain and Ireland :—

1924, . . .	$2\frac{2}{3}$ million tons.
1929, . . .	4 ,, ,,
1930, . . .	$4\frac{1}{3}$,, ,,
1931, . . .	$4\frac{1}{2}$,, ,, .

Specification Suggestions.

For all ordinary work a clause in the general specifications stating that the cement shall comply with the requirements of *B.S. Specification No. 12* is all that is required. For special work the various items could be enumerated in detail and higher test figures, etc., demanded. The limits of such a specification have already been indicated. For a rapid-hardening Portland cement the engineer would have to prepare his own specification, or he could use B.S.S. No. 12 with suitable modifications. For aluminous cement the writer suggests that the tentative specification issued by the *Institution of Structural Engineers* should be adopted. For coloured cements B.S.S. No. 12 will usually be found sufficient safeguard so long as it is coupled with the proviso that the colour shall be fast to light and shall be absolutely inert in the presence of cement and water.

CHAPTER III.

TYPES OF AGGREGATES.

General.

Definition.—There have been many more or less satisfactory definitions for "aggregate," but the best is probably that adopted in the "*Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete, U.S.A., 1924.*" This states that "aggregate" may be defined as "inert material which is mixed with Portland cement and water to produce concrete ; in general, aggregate consists of sand, pebbles, gravel, crushed stone, or similar materials." This definition is sufficiently elastic to include many materials not usually regarded as concrete aggregates, but any restricted requirements can be dealt with in a suitable specification.

Choice of Materials.—Since about four-fifths of an ordinary piece of concrete consists of aggregates, it is easy to realise that an investigation of possible supplies may be of the utmost importance. Provided crushing strengths are not too low, almost any natural rock demands consideration, and the final choice of material will often be ruled by economic factors. Assuming some convenient measure of comparison, a case may occur where aggregate A is 95 per cent. efficient but is 100 miles away, whereas aggregate B is 85 per cent. efficient but is "on the spot." A costs 20/- per ton, but B costs only 7/6 per ton. Other things being equal, it appears that the extra 10 per cent. efficiency will cost 12/6 per ton of stone used. In such an instance it will probably pay to use stone B, with a slightly richer concrete, or compensate in some other way for the deficiency.

This example has not been given to suggest that

unsuitable aggregates may be used. A stone may be inferior without being unsuitable. Economics play an important part in this question of choice of materials, and all relevant factors require consideration.

General Requirements.—Aggregate suitable for making concrete must possess certain characteristics, some of which are fairly obvious, and others of which are not quite so evident. Ideal requirements can only be obtained on comparatively rare occasions, and, on most jobs, economic conditions will call for the use of materials somewhat less than perfect. Intensive and extensive research has enabled us to state with a fair degree of success just what properties are essential, and how variations will affect the resulting concrete. However, there is still much to be done, as will be shown later.

For general work an aggregate must be

Clean,
Structurally sound,
Suitably graded,
Weather-resisting,
Inert in the presence of water.

For special work, particular properties become of paramount importance: good wearing qualities for road surfaces (this question is not as simple as it appears at first sight), fire resisting qualities for fireproof constructions, lightness for lightweight constructions, etc.

CHARACTERISTICS OF COARSE AGGREGATES.

The characteristics of coarse aggregates are discussed briefly in the two following summaries of results obtained in America and Germany. The subject is too large to be considered in detail in the present book, and for results of tests, etc. the reader is referred to the original papers.

American Tests.—As a result of an investigation of this problem, the following conclusions were presented recently by S. Walker [20] :—

"(1) Aggregate characteristics have important effects on the quality of concrete, but these generally are of less

importance than effects which may result from variations in proportioning, mixing, placing and curing the concrete.

" (2) Aggregate characteristics which affect the quality of concrete are, in general, common to different types of materials. Studies of them should be made without reference to type : comparisons of miscellaneous aggregates of different types lead to inconclusive results.

" (3) Studies of aggregate characteristics should include consideration of the significance of durability, hardness and strength of aggregate particles, surface texture, shape, deleterious substances and grading.

" (4) Except for durability and certain deleterious substances, there are, in general, no significant aggregate characteristics the effect of which cannot be compensated for by relatively minor changes in the proportions. The selection of aggregates is, therefore, almost entirely a problem of economics.

" (5) The indications of the few tests available are that aggregates which are unsound for a given condition of exposure will cause the eventual disintegration of concrete exposed to the same conditions—the mortar offering relatively little protection.

" (6) Carefully controlled tests of different aggregates falling within the range of quality of those commonly used for concrete have shown differences in transverse strength of concrete of approximately 25 per cent. due to aggregate characteristics other than grading, soundness or deleterious substances. A rough estimate would place the responsibility on strength of particle for about one-half of this difference and one-half on surface texture. For the same conditions comparatively minor differences in compressive strength occurred, and these variations showed no consistent relationships to aggregate characteristics.

" (7) The principal effect of the more common so-called deleterious substances, such as soft and friable particles, is on the appearance of concrete for a comparatively wide range in quantity present. Clay and organic matter cause varying effects depending on conditions : their presence in aggregates may be reduced to negligible amounts by thorough washing.

"(8) Variations in grading of coarse aggregates cause variations in economy, workability, yield and strength of concrete. However, their effects on strength are much less than generally assumed. The importance of using the larger sizes of aggregate has been over-emphasised."

German Tests.—In "*Zement*," 1929,[21] K. Pfletschinger presents the report of an investigation carried out at the *Institute for Concrete and Reinforced Concrete* (Institut fur Beton und Eisenbeton), *Karlsruhe*, for the purpose of examining systematically the effects of the following aggregate variables upon the physical properties of concrete :—(1) Size and grading ; (2) shape ; (3) structure (porosity and water absorption) ; and (4) proportion of coarse aggregate. The same fine aggregate was used throughout. In all series of tests either the water-cement ratio or the consistency was kept constant. Specimens were submitted to compression, bending, permeability, workability and shrinkage tests. The author draws the following conclusions from the results obtained :—

Compressive strength is influenced by each of the variables considered. It was found, with few exceptions, that ballast has fewer voids than broken stone, and therefore requires less fine aggregate. A ballast concrete mix thus will require less water to obtain a given consistency. This difference is accentuated further by the greater surface to be wetted in the case of broken stone, by the greater water absorption of the material and by the presence of fine dust adhering to the fragments. For equal cement contents this difference in the amount of mixing water required for either plastic or pourable concrete causes broken stone concrete to be inferior to ballast concrete as regards compressive strength. The larger the coarse aggregate, the less mixing water is required for mixes of equal sand content, and the more workable is the concrete. The grading of the coarse aggregate has no direct influence upon compressive strength, but in poured concrete well-graded aggregate reduces segregation. The structure of the aggregate has a considerable influence on the amount of mixing water required, and thus on strength. The ballast concretes give the highest compressive strengths. The amount of coarse aggregate is

of importance. Large proportions of coarse aggregate reduce the amount of mixing water and increase compressive strength. With very few exceptions, the strength of the concrete was always greater than that of its constituent mortar. The differences were considerable, amounting with broken stone concretes to 45 per cent. The water-cement to strength relation was found to hold only for concretes containing aggregates of the same type. Tensile strength, as measured by the bending test, is affected in much the same way as compressive strength ; slightly higher strengths were obtained, however, with specimens containing long, pointed stone fragments. In plastic mixes the broken stone gives slightly better results than the ballast, but in pourable mixes the reverse obtains. Elasticity, shrinkage and permeability are all affected by the type of coarse aggregate. Here, again, the amount of mixing water is the dominating factor ; as regards these properties, ballast concrete is superior to broken stone concrete. Workability, both when using ballast and broken stone, is affected to a small degree by grading ; the adverse effect is especially marked when there is an excess of the largest sizes. From the point of view of workability, ballast is superior to broken stone.

Comments.—It will be seen that this question of aggregate characteristics is very involved, and to those interested in looking further into the subject, the following remarks are worthy of note :—

Tests by D. A. Abrams [22] have indicated that approximately the same average strengths and depths of wear were obtained from different aggregates, such as pebble, limestone, granite, trap, sandstone, blast-furnace slag, flint and marble. Similar test results were obtained by F. E. Giesecke.[23] The influence of the type of coarse aggregate is also pointed out by Gilkey.[24]

Failures Due to Aggregates.

When the failure of a concrete is due to the aggregate, it will usually be found that the grading is unsuitable or that the aggregate is unsuited chemically for the making

of concrete. The question of grading has been referred to already, and there is no reason why natural stone aggregates should cause failures on this account. It is necessary only to specify the correct grading, see that this grading is supplied, and have the usual supervision to ensure that segregation does not occur.

Aggregates which cause the failure of concrete due to being chemically unsuitable are more difficult to deal with adequately. With very few exceptions (at the moment the writer can recall only one, namely, a few of the spars containing small quantities of zinc compounds which react with the cement and delay or prevent setting of the concrete), natural stone aggregates are chemically inert in the presence of cement and water. Many of the artificial aggregates are not inert. Slags may or may not (and this uncertainty is the trouble) be free from harmful amounts of injurious chemical constituents. Several concrete failures have been traced to the presence of an excessive quantity of "sulphide" in slag used as the aggregate. Certain types of broken brick have been known to cause serious "spalling" in the concrete. Cinders and clinkers have also caused failures of varying degree.

Occurrence of Aggregates.

Natural and Artificial.—Aggregates suitable for making concrete may be natural or artificial. A detailed investigation of either group is quite beyond the scope of this book, but general outlines will be indicated. For further information on the natural aggregates or "rocks," reference should be made to the various geological text-books and technical articles and papers.

Commercial Terms.—It is obvious [25] that it is of little use to gain information about the behaviour of aggregates either by controlled experiments or special investigations, or from actual experiences with concrete structures themselves unless the materials concerned are accurately described and properly named. Otherwise the information cannot be applied to other materials of a similar nature,

nor can it be used as a means of future guidance. The question of nomenclature is thus one of far more than academic importance. In particular it is strongly to be urged that specifications should describe and name materials with sufficient detail and discrimination to avoid the misconceptions that surround many of the commercial terms unfortunately in common use. Terms like ballast, granite, and trap-rock, unless qualified or otherwise made unequivocal, are often quite misleading. Ballast does not mean only "Thames ballast" (flint gravel), but it includes also gravels composed of quartzite, sandstone, limestone, granite, and other pebbles. One type of pebble may predominate, and the aggregate, especially if crushed, is then equivalent to one composed of crushed fragments of the rock-type represented. Many gravels, however, are of a composite nature, and are then equivalent to a correspondingly mixed aggregate. As a commercial term "granite" is applied not only to granite in its broadest geological sense, or to rocks like diorite and gneiss, but also to rocks as different from these as limestone, quartzite or schist (sedimentary and metamorphic), dolerite, and other igneous rocks. It thus overlaps in meaning with "whinstone," another common term, which includes dolerites and basalts, and similar dark, fine-grained igneous rocks. The term "trap" unfortunately is so widely applied as to be of very little descriptive value. It includes not only the "whinstones," and their altered analogues the "greenstones," but also a miscellaneous series of other types which may behave very differently as aggregates. Less than a score of names would, with suitable mineralogical and structural prefixes, be adequate to designate for most purposes the majority of the chief rocks used for concrete—provided always that they were properly applied. Surely it is desirable that those in charge of concrete work should know these terms and the chief properties which their application to a rock implies.

Geological Classification of Rocks.—Rocks [26] fall naturally into two main groups, according as they have been formed by geological processes which belong essentially to the surface of the earth, or by processes belonging to the interior

of the earth. Each group may be divided further according to the kind of process concerned in the genesis of each class of rock. The following scheme, though not quite complete, includes almost all possible types of rocks, and indicates at a glance their differences and inter-relations.

Rocks Formed by Internal Processes.	(a) *Igneous Rocks*, formed by solidification from a state of fusion, *e.g.*, Granites and Basalts.
	(b) *Metamorphic Rocks*, formed by the recrystallisation of pre-existing rocks, igneous or sedimentary, due to the action of internal heat and pressure, but without actual fusion, *e.g.*, Crystalline Schists.
Rocks Formed by External Processes (Sedimentary Rocks).	(a) *Mechanical Sediments*, formed by the aggregation of fragments of pre-existing rocks, *e.g.*, Gravels, Sands and Sandstones.
	(b) *Chemical Deposits*, formed by direct precipitation from solutions, *e.g.*, Beds of Rock Salt.
	(c) *Organic Deposits*, formed from solutions or otherwise by the agency of organisms, *e.g.*, Limestones and Coal.

Artificial Aggregates.

Breeze and Clinker.—The evidence [27] that has been presented has shown that the presence of certain types of coal in a concrete leads to the occurrence of marked expansional movements which cause ultimate failure. The examination of many breezes and clinkers, and of concretes made from such aggregates, has demonstrated that a relatively high proportion of combustible matter is often present, and that unburnt coal may in some cases be detected. Without any further evidence it would be clear that failures due to the presence of such types of unburnt coals are probable and to be expected. The examination of breeze concrete failures and of unsound breezes has shown that in every case the troubles experienced are attributable to the presence of dangerous coals. In only one case was there any suspicion of unsoundness due to sulphur content, and in this case it appears probable that the effects produced were predominantly due to coal.

The work on sulphur compounds in breeze and clinker has indicated that, when the sulphide sulphur is present as a finely divided active powder, a limit of 0·4 per cent. sulphide sulphur is safe. That sulphide sulphur could occur in practice in such an active condition is unlikely, since mere exposure to the weather for a short time would suffice to oxidise it to a considerable extent. When present in a fused or sintered condition considerably larger sulphide contents produce no deleterious effects. Rather similar results have been obtained with calcium sulphate. Although, therefore, sulphur cannot be ruled out as the cause of occasional breeze failures, the preponderating weight of evidence points to this being a rare cause, and to the great majority of failures being produced by the presence of certain types of coal. Specification limits for sulphur content of breeze and clinker have been suggested, but no analyses for these are included in the general methods of test and, excepting in cases where the most rigid precautions are necessary, it is not recommended that any such analyses be carried out. In cases where such rigid precautions are essential, the suitability at all of breeze or clinker may be questionable.

Broken Brick.—Broken brick is, in general, suitable as an aggregate for concrete, but certain precautions are necessary. It should be clean, *i.e.* free from lime, plaster, etc. In some instances it has been found that brickwork which has been pulled down and broken for use as aggregate has been quite unsuitable, as the bricks were coated with calcium sulphate in the form of plaster. Calcium sulphate in concrete will cause disintegration. The same remarks apply to coatings of "Keene's," "Sirapite," etc. In the presence of water the plaster reacts with the aluminates in Portland cement, forming sulpho-aluminate of lime, and causing a volume increase. The amount of this expansion depends upon quantity of water, the quantity of calcium sulphate, etc., and the resulting movement may or may not be important. A certain amount of calcium sulphate virtually may be harmless in concrete which remains quite dry after setting, but the same quantity may destroy the concrete if in a wet position.

Some bricks, made from clay containing pyrites, are

liable to contain sulphur in an active form. Aggregates from such a source may swell and crack after the concrete has set, particularly in damp situations. A further danger with some bricks is the presence of unslaked lime. Soft bricks may be found unsuitable ; and any excess quantity of dust should be removed.

Broken brick is exceedingly porous and should be well soaked with water before use. Otherwise the water required for the setting action of the cement will be absorbed by the brick, thus causing imperfect hardening and consequent cracking, etc. of the concrete.

Burnt Ballast.[28]—The ordinary burnt clay-ballast, as a rule, is not burnt hard enough, and produces a concrete of indifferent quality. If, however, it is well burnt, it becomes brick-like and is suitable. For making burnt ballast a clay suitable for brick-making should be used, and the fuel should be slack, *i.e.* small coal, or coke free from sulphur or other deleterious substances. The lumps of clay are arranged with layers of fuel every 6 inches of thickness. About $1\frac{1}{2}$ cwt. of fuel should be allowed to every cubic yard of clay.

Slag.[29]—Two disadvantages are found in the usual acid slags, more particularly those having a very high silica content. One is due to their physical character and the other to their chemical character. Glasses fracture with smooth conchoidal surfaces, quite different from the irregular fractures of finely crystalline bodies ; for this reason, and owing to the lack of adhesion between the cement and the aggregate, they produce rather weak concretes. The other disadvantage is that acid slags are very inert chemically. Basic slags are acted upon slightly by the water contained in concrete, and this binds the aggregate to the cement ; but acid slags are so inactive, so far as water is concerned, that this action is negligible. Despite these objections, however, it is found in practice that acid slags make sound concrete of good strength provided that the silica content is not excessively high.

It is sometimes thought that basic slags are dangerous in concrete, but this danger has been very much overrated. A slag which is unstable will commence to powder-down

within about 14 days after cooling, and slags which show even a slight tendency to decompose in this period will continue to disintegrate over a long period, or until the process is complete. On the other hand, general experience shows that a slag which has remained stable for over 14 days, and shows no incipient decomposition in this time, will remain stable indefinitely. It should therefore almost always be possible to detect a disintegrating slag and not use it. It is true that many of the more basic slags which do not powder-down within a week or 14 days are really unstable, but, under normal conditions, such slags will continue indefinitely in this "metastable" state. If at any time, however, a rise in temperature occurred, such as, for instance, exposure to a fire, the instability of the slag might manifest itself.

From the foregoing discussion it is clear that well-seasoned slags are to be preferred as aggregates, since a disintegrating slag can then be distinguished easily, and there is little or no danger of a good slag commencing to decompose after use. Some American firms store a slag for periods of from six to twelve months before selling for use as aggregate. It would appear, for the same reasons, that non-decomposed slag from old slag heaps would provide a safe aggregate, but such material must be used only when it has been ascertained that it is not contaminated with ashes, or wood and vegetable refuse.

The specific gravity of a slag has sometimes been applied as a criterion to determine suitability, but this forms no definite test.

A real danger in the use of basic slags arises from their setting properties. Limey slags are acted upon by water, the extent of this action increasing with the lime content of the slag. Large lumps will be affected only superficially by water, while very fine slag will act as a cement. Any medium-sized particles present will not hydrate at once, but will be acted on slowly by the water after the cement has set. Owing to the expansion produced on hydration, this will set up dangerous stresses in the concrete, possibly leading to failure. It is difficult to decide exactly what fineness of particle constitutes a dangerous material, and

it is therefore accepted by nearly all investigators that, when using basic slags as aggregates, all the fine particles, from sand fineness downwards, should be removed and replaced by ordinary sand.

In view of the disadvantages inherent in both very acid and highly basic slags, it is wise to use only those of intermediate composition, when concrete may safely be prepared with good strength and permanence. It is also desirable, if possible, to use a well-matured slag.

CHAPTER IV.

ANALYSIS OF AGGREGATES.

Samples.

Unless sampling is done efficiently, tests will be of little or no value, and the results may be quite misleading. A sample four or even eight times as much as the required amount should be taken from the supplies of material and reduced by the usual method of "quartering." "Quartering" is done by mixing thoroughly, arranging the material in the form of a circular pile, dividing it into quarters and removing diagonally opposite quarters. This operation is repeated with the portion left, and the next time the other two corners are taken out, and so on.

Particular care is necessary when taking samples from lorries, wagons, etc., as the movement during travel causes a certain amount of segregation. The ideal method is to dig a hole to the bottom of the vehicle and drag the point of a shovel up the side from bottom to top. This procedure should be followed until there is sufficient material for quartering. A similar method could be adopted when taking a sample from a pit face, the material being obtained by scooping vertical troughs along the face at approximately equal distances apart.

Samples for testing should be large enough to enable all the tests required to be carried out without having to send a further supply of material. For full tests on aggregate it is advisable to send at least 1 cwt. of the coarse aggregate, and ½ cwt. of the fine aggregate. Information which is as detailed as possible should be sent with the samples, giving source of supply, extent, etc. Where

variations in the source are suspected, several samples are advisable. It should be appreciated that a test of an aggregate is only of value in-so-far as the sample is a true representation of the supply.

TYPES OF ANALYSIS.

The analysis of aggregate may be made in three different ways :—

(1) Chemical,
(2) Mineralogical,
(3) Mechanical.

Chemical Analysis.—A chemical analysis of an aggregate is of minor importance from our point of view. In almost all cases the analysis of a natural sand will show 80 to 99 per cent. of silica. The chief remaining constituents are alumina, iron oxide, magnesia, lime, soda, potash.

Mineralogical Analysis.—This method is not of great importance to the concrete worker except in-so-far as he wishes to know when the clayey decomposition products of the felspars, etc. are present.

The mineralogical composition [30] of a sand is the fundamental factor in its mortar-making qualities, since not only its durability, and hence the durability of the mortar, but the size and gradation of the grains, the nature of the grain surfaces, the strength of the grains themselves, and all the other factors which affect the strength of the mortar, are more or less directly dependent on the nature of the component materials of the sand.

Mechanical Analysis.—The mechanical analysis of an aggregate is of prime importance, as will be shown later, and the following notes are therefore given in great detail. The importance of this subject to the producer of aggregate for concrete can scarcely be over-estimated.

GRADING OF AGGREGATES.

The correct grading of aggregates for concrete is a matter which, in this country, is not receiving the attention it deserves. There are still specifications issued for concrete work which do not refer to the grading of the aggregate at all ; others refer to it in a general, off-hand way ; whilst a few indicate that a genuine attempt has been made to specify aggregate which will make a really good concrete.

In this discussion " grading " is considered in its broadest sense, and the various points which arise will be dealt with in detail. The value of suitably-graded aggregates is being slowly, but surely, appreciated, and it is interesting to note that many of the larger firms are prepared to deliver aggregates to the job in various screened sizes to prevent segregation. Materials may be properly graded and mixed at the quarry, but if segregation should occur and remain uncorrected when the aggregate is placed in the mixer, some batches will consist of coarse particles with high voids, whilst others will consist of finer particles with equally high voids. Thus, the benefits derived from careful grading at the quarry may be entirely nullified by segregation afterwards.

The greater attention being paid to these matters of grading and segregation will result in better concrete at less cost.

Value of Coarse Material.—Considering compressive strength alone, it is safe to say that, within the limits of workability, the greater the percentage of coarser particles in an aggregate the greater will be the strength. Also, for equal proportions of cement to aggregate, the concrete having the greater percentage of coarser material will, in general, show less absorption. This does not mean that the largest permissible size of aggregate may be increased in quantity *ad lib.*, without reference to the rest of the mix, but it does mean that a well-graded stone having a higher upper limit in size will give a better concrete than one having a low upper limit.

Water-Ratio Theory.—When considering the strength of concrete, we should not lose sight of the basic fact that

the amount of water used in the mix has a direct effect on the resulting concrete strength. The strength of a concrete mixture depends on the quantity of mixing water in the batch, expressed as a ratio to the quantity of cement, so long as the concrete is workable and the aggregates are clean and structurally sound. The strength decreases as the water ratio increases.

D. A. Abrams, who was responsible for the water-ratio theory, found that the sieve analysis of an aggregate could be used as a basis for proportioning aggregate in concrete, and he developed a function known as the "fineness modulus." Aggregates having similar concrete-making qualities may be obtained in an endless variety of gradings, but it should not be overlooked that only gradings between definite limits can give a certain value of the "fineness modulus." This will readily be understood by a consideration of the "fineness moduli" for particular aggregates. It is important to realise that concretes having similar strengths may be made by combining coarse and fine grades having widely different size or grading. The grading necessary for producing concrete having maximum density is not quite so coarse as that required for maximum strength, but the difference is slight, and in practice may usually be neglected, particularly since a little strength can be sacrificed advantageously for increased density, with its accompanying advantages. This discrepancy between grading for density and grading for strength becomes greater as the mix becomes richer.

Fineness Modulus.—This, as already stated, is a function of the sieve analysis of an aggregate, and is obtained by dividing by 100 the sum of the percentages retained on each of the following sieves :—

$3''$, $1\frac{1}{2}''$, $\frac{3}{4}''$, $\frac{3}{8}''$, $\frac{3}{16}''$, $\frac{3}{32}''$, $\frac{3}{64}''$, No. 30, No. 50, No. 100.

These are English sieves and may easily be obtained. It will be noticed that the linear opening of any sieve is half that of the next larger sieve.

A sample of the aggregate should be dried, weighed, and passed through these sieves, the "fineness modulus" being found as shown in the following table :—

Fineness Modulus.	
Sieve.	Percentage Retained.
100	95
50	76
30	68
$\frac{3}{64}''$	55
$\frac{3}{32}''$	22
$\frac{3}{16}''$	8
$\frac{3}{8}''$	2
$\frac{3}{4}''$	...
$1\frac{1}{2}''$	...
$3''$	...
Total .	326

$$\text{Fineness Modulus} = \frac{326}{100} = 3{\cdot}26.$$

An understanding of the "fineness modulus" will help us to realise just how the grading of an aggregate affects the concrete strength, but it is not essential that this method be used to obtain good results. For this reason too much stress will not be laid on the use of the method, particularly as it has not yet been adopted in a general way in this country.

Sieves for Fineness Modulus.—English sieves are slightly different from the American sieves, as indicated in the following table :—

Sieves for Fineness Modulus of Aggregate.			
English Sieves.		American Sieves.	
Name.	Size of Aperture in Inches.	Size of Aperture in Inches.	Name.
100	0·0060	0·0059	100
50	0·0116	0·0117	50
30	0·0233	0·0232	30
$\frac{3}{64}''$	0·0474	0·0469	16
$\frac{3}{32}''$	0·093	0·0937	8
$\frac{3}{16}''$	0·186	0·187	4

Values of Fineness Modulus.—Maximum permissible values of the fineness modulus are given in the following table, which is based on the requirements for gravel aggregate in ordinary reinforced concrete work :—

Maximum Values of Fineness Modulus.				
Mix.	Size of Aggregate.			
Agg. : Cem.	0–4.	0–⅜″.	0–¾″.	0–1½″
6 : 1	3·30	4·05	4·85	5·65
4 : 1	3·60	4·40	5·20	6·00
2 : 1	4·20	5·05	5·90	6·70

For other conditions the following allowances should be made :—

(1) If crushed stone or slag is used as coarse aggregate, reduce values in table by 0·25. For crushed material consisting of unusually flat or elongated particles, reduce values by 0·40.

(2) For pebbles consisting of flat particles, reduce values by 0·25.

(3) If stone screenings are used as fine aggregate, reduce values by 0·25.

(4) For the top course in concrete roads, reduce values by 0·25. If finishing is done by mechanical means, this reduction need not be made.

It is undesirable for sand used in concrete work to have a fineness modulus lower than 1·5.

Strength and Yield.—The specification of a concrete mix may be regarded partly as the concern of the engineer and partly the concern of the contractor, the former being concerned with the strength of the concrete, and the latter with the economy of the mix. These two points of view may be considered separately, and the engineer can, in general, be safeguarded as far as the strength is concerned,

by specifying the ratio of water to cement. Working on this specification the contractor can, within limits fixed by the engineer, use any grading of aggregate he wishes. He will, therefore, make a special point of getting as good a grading as possible, since this will result in a better concrete and a larger yield per cwt. of cement. This point will be referred to again later when dealing with the design of concrete mixes. The point to notice here is that the grading of aggregate becomes important to the contractor since it affects appreciably the cost of his concrete.

Suggestions on Grading.—It is advisable to have at least two grades of aggregate, *i.e.*, coarse aggregate and fine aggregate, or, say, stone and sand. On high-class work the tendency is to have three or even four grades, as this ensures better concrete in every way. There are numerous specifications for gradings, and whilst there is no entire agreement on the matter, the following suggestions will be found helpful.

The sand should be graded so that it conforms to the following (percentages by weight) :—

95 per cent. to pass $\frac{3}{16}$-inch screen.

Not more than 30 per cent. and not less than 10 per cent. to pass a 50-mesh sieve.

Not more than 10 per cent. to pass a 180-mesh sieve.

The stone should be graded so that it conforms to the following :—

Maximum size $\frac{3}{4}$-inch (or other value).

95 per cent. to pass $\frac{3}{4}$-inch screen.

Not more than 10 per cent. to pass $\frac{3}{16}$-inch screen.

It should be uniformly graded within these limits.

It is found in practice that approximately equal quantities of each size make a good dense concrete.

The following table, taken from the "*Report of the Joint Committee on Standard Specifications for Concrete and*

Reinforced Concrete," 1924, indicates desirable gradings for coarse aggregates of certain nominal maximum sizes.

Nominal Maximum Size of Aggregate, Inches.	Percentage by Weight passing through Standard Sieves with Square Openings.						Percentage passing	
	3″	2″	1½″	1″	¾″	½″	No. 4 Sieve.	No. 8 Sieve.
							Not more than	Not more than
3	95	...	40–75	...	...	...	10	5
2	...	95	...	40–75	...	...	10	5
1½	...	...	95	...	40–75	...	10	5
1	...	...	...	95	...	...	10	5
¾	...	...	...	...	95	...	10	5
½	...	...	...	...	...	95	10	5

Workability.—" Workability " is rather hard to define. Concrete that will go easily into the forms, fill all corners without too much puddling or spading, and show a finish free from honeycombing, etc., is " workable." Among other things, " workability " depends upon

(1) Quantity of mixing water,
(2) Quantity of cement,
(3) Size and grading of aggregates.

A certain amount of fluidity is always necessary, but it cannot be obtained by adding more water to the mix without lowering the strength. When more water is added it is necessary to add more cement, thus increasing the cost of the concrete.

The best way of getting workable concrete without increasing the amount of cement used is to select aggregates that will give the greatest workability with the least amount of mixing water, and then to proportion them to the best advantage.

Combining Aggregate.—It is important to combine the fine and coarse aggregates in the proper ratios. Too much coarse aggregate will give a mixture that is too harsh and that will result in honeycombing. A slight excess of fine material will give a smoother, more workable mix, and will

result in better surfaces. Too much fine material, however, will produce porous concrete. If the proportions of fine and coarse aggregates are kept within the limits shown in the following table, good concrete with workable consistencies, will usually be obtained.

Max. Size of Coarse Aggregate in Inches.	Ratio of Coarse to Fine Aggregate.	
	Maximum.	Minimum.
$\frac{3}{8}$	0·8	0·4
$\frac{3}{4}$	1·5	0·6
1 and over	2·0	1·0

Actual Example.—C. L. McKerson reports that during 1927 he had the opportunity of comparing concretes on two jobs constructed in the same locality, at the same time, and using the same cement. The sand and rock in each case were of high quality ; in one case a high standard of grading was maintained, with low voids ; in the other case excessively fine sand was used. The amount of cement used per cubic yard of concrete was the same on each job. The average compressive strengths with the well-graded material averaged nearly 5,000 lbs. per square inch, and on the job with poorly graded material about 2,000 lbs. per square inch. A somewhat wetter consistency was used on the job with the fine material, but the slump was reported to be less than 2 inches.

Quarry Owners.—It is apparent that quarry owners can render great assistance in improving the quality of concrete, and that for so doing they can reasonably request some share of the saving effected, in proportion as it increases their cost of production. The service can best be rendered by assisting in establishing specification standards which will ensure the use of sand and stone with low voids.

Combining Aggregates by Fineness Modulus Method.—Two aggregates whose fineness moduli have been calculated will give a definite value for the fineness modulus of the

mixed aggregate when they are combined in any particular ratio.

Let A = Fineness modulus of stone.
B = ,, ,, ,, sand.
X = Ratio of volume of stone to sum of volumes of separate aggregates.
Y = Ratio of volume of sand to sum of volumes of separate aggregates.
M = Fineness modulus of combined aggregate.

Then $$M = A.X + B.Y.$$

For three aggregates this equation becomes

$$M = A.X + B.Y + C.Z,$$

and so on.

To obtain the proportions for a given fineness modulus the above formula can be modified, when we get

$$X = \frac{M - B}{A - B}.$$

For more than two materials this solution can be used, but it will have to be applied in steps by taking two aggregates at a time.

Grading of Aggregates for Blocks.—Generally [31] the grading necessary for the strongest concrete is such that a rough surface is produced. This rough texture makes the blocks appear inferior in quality, and it will often be advisable to produce a smoother article at the expense of a little strength. This can be done by using aggregates of the largest possible size, as this will increase the fineness modulus, so that for a given fineness modulus of mixed aggregates a bigger percentage of sand may be used. This increased quantity of sand will enable a smoother block to be made. Half the thickness of the thinnest web of the concrete block should be the size of the largest piece of aggregate.

The results of a series of tests on concrete building tiles carried out at the *Lewis Institute* show forcibly the advantage of properly graded aggregates in the manufacture of

concrete products. The tiles were made at a concrete products plant under ordinary and identical operating conditions. The grading of the aggregate was varied by using different proportions of 0 to No. 4 sand and No. 4 to $\frac{3}{8}$-inch pebbles. Results from these different gradings used with one part of cement to three parts of aggregate, and with one part of cement to five parts of aggregate, are

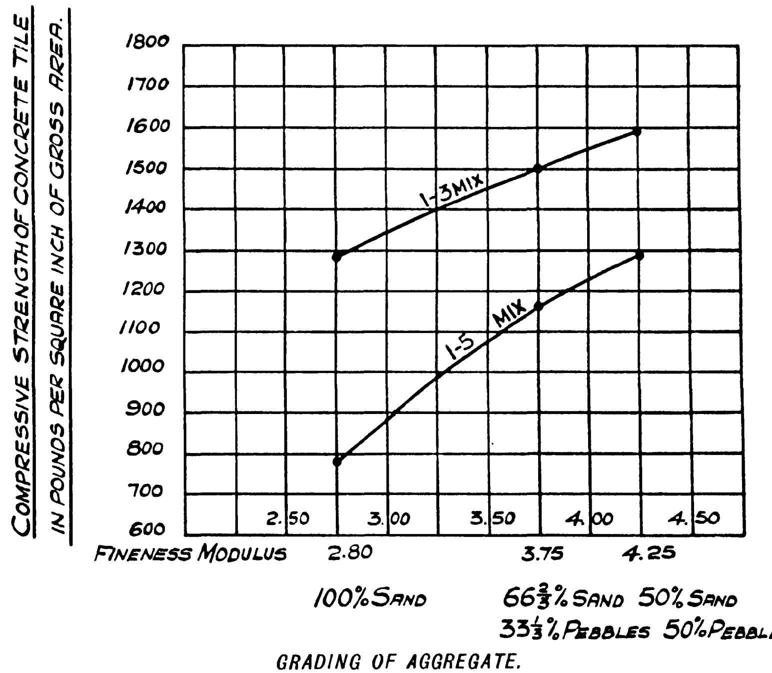

Fig. 2.—Grading of Aggregate and Compressive Strength of Cement Tile.

shown in Fig. 2. The tiles were tested at 28 days. A strength of 1,280 lbs. per square inch of gross area was obtained with a mixture of one part of cement to five parts of aggregate (having a fineness modulus of 4·25) composed of 50 per cent. sand and 50 per cent. pebbles. It was necessary to use a mixture of one part of cement to three

parts of aggregate (having a fineness modulus of 2·80) composed of all sand to obtain the same strength.

The effect of aggregate grading on the strength of concrete is also well demonstrated by the results of the following tests made upon concrete bricks and concrete blocks. It was found that to manufacture concrete bricks with a compressive strength of 1,500 lbs. per square inch when 28 days old—

an aggregate of	2·75 F.M.	would require a	1 : 5	mix.
,,	3·25	,, ,,	1 : 7	,,
,,	4·25	,, ,,	1 : 9	,,

Grading of Sands and Bulk.—The volume of a given weight of sand will depend, among other things, on the grading of the particles. Spheres of equal diameter may be hand-packed in a special container so as to give three distinct " bulks." The lowest packing gives 47·6 per cent. of voids, the intermediate packing 39·5 per cent. of voids, and the closest packing 26·0 per cent. of voids. Experimental results published a few years ago by H. Jackson [32] in the " *Structural Engineer* " showed that the average voids amounted to 39·3 per cent. when using gunshot of uniform diameter, with sizes varying from $\frac{1}{16}$-inch to $\frac{1}{4}$-inch. The shot was run into a cylinder, and even when there was a gentle ramming as the particles were poured in, there was very little difference in the result. The value of 39·3 per cent. obtained is in close agreement with that of 39·5 per cent. obtained by the " intermediate " hand-packing of spheres. This method of packing, therefore, is that adopted when the particles are poured or rammed.

The variations in bulk due to differences in grading are not as great as is commonly assumed. If we take the " intermediate " packing and so obtain voids of, say, 40 per cent., it is possible when packing by hand to fill in the voids to a large extent by smaller particles, and so on with still finer particles. This method of packing would result in a sand having a much lower percentage of voids than ever occurs in practice.

To illustrate the limits which can be obtained artificially, J. E. Worsdale [33] carried out a series of experiments,

separating a sample of river sand into its various grades and determining their void contents, obtaining results of about 38 to 39 per cent. in each case. But almost any mixture of the various grades brought the result down to about 35 per cent., even when the two grades used were nearly equal in size. A uniform grading gave a result of 32·5 per cent., and the very lowest which could be obtained was 28·4 per cent., where the largest and smallest grains were mixed together without any intermediate sizes being present. The two extreme cases are never obtained in practice, and a large number of void determinations performed on commercial sands have revealed the fact that only quite small variations in void content are experienced, the lower limit being about 32 per cent. and the upper limit about 35 per cent. The reason the theoretical result is not in accordance with the facts is that the smaller sizes of particles refuse merely to nestle in the voids between the larger ones, but wedge the latter apart. The effect of grading upon bulk is thus seen to be of only small degree.

There is a further point in considering the void content of grits, and that is that the value is not necessarily the same under wet as under dry conditions. If we imagine the case of a flaky type of crushed stone, the voids measured dry, without shaking, will be very high, perhaps over 50 per cent., and yet under practical conditions, with the admixture of the lubricating cement paste, the voids will reduce to the more normal figure of 34-35 per cent.

Sand Content and Water Ratio.—The results of tests [34] on 160 different combinations of cements and aggregates indicate that for each cement there is a characteristic water-cement ratio strength relationship, similar to that expressed by

$$S = \frac{14{,}000}{7^x}$$

where x is the water-cement ratio. This has been termed the "normal" water-cement ratio strength relation. The tests showed that, to obtain strengths at least equal to that indicated by this "normal" relationship, the amount of sand required varied from 33 to 50 per cent.

of the total aggregate, that these percentages are the smallest that give workable mixes, and that they correspond to the maximum economy of cement. A specification is proposed embodying these results, and which would specify that the aggregate contain at least 33 per cent. sand, that when this minimum of sand is used, the volume of the coarse aggregate of any one size should not exceed twice nor be less than one-third that of the next smaller size, no lower limit, however, being placed on the largest material, and that in cases in which certain sizes of aggregate are omitted, the sand content should be between 33 and 50 per cent. By " aggregate of any one size " is meant the amount of aggregate passing any given sieve and retained on the next smaller sieve.

CHAPTER V.

WEAR OF AGGREGATES AND CONCRETE.

AGGREGATES.

Different Tests Required.—Suppose the problem is to get a concrete possessing a high degree of resistance to wear. Then one way, and the easiest way, is to settle the aggregate question by stating that it shall be granite from a particular quarry. Assuming everything else is in order, this method will ensure good results, but it has the effect of ruling out other aggregates, which may be cheaper (owing to distance of work from the named source of supply) and yet be quite satisfactory.

When dealing with crushed stone for macadam roads a standard attrition test was developed. This test, known as the " Deval test," was found to give useful results and was universally adopted. Automatically it came to be used when testing all kinds of aggregate for concrete wearing surfaces. This is unfortunate because (1) The standard Deval test for crushed stone cannot be applied to gravel because of the requirements for shape and size of particles composing the prepared test samples, (2) Much less rigid requirements than those of the Deval test are required for aggregate for concrete, as resistance to wear is not so important as soundness, although generally the softer stones do not make as sound concrete as the harder ones. Also, the value of such a test is only relative, as it usually is necessary to set abrasive limits to suit local materials.

Terms Used.—Some confusion may arise due to the fact that the tests in America have not the same names as here. This is shown in the following table :—

Test.	English Name.	American Name.
Deval	Attrition test.	Abrasion test.
Dorry	Abrasion test.	Hardness test.

Rocks.

Deval Attrition Test.—As indicated already, this test is made with the idea of determining how a crushed stone will wear in a macadam road. The following procedure is that adopted at the *National Physical Laboratory*, Teddington :—

The machine consists [35] of four cylinders, $7\frac{1}{2}''$ in diameter and $14''$ long, mounted on a frame, with their axes at 30 degrees to the axis of rotation. 11 lbs. of rock (as near 50 pieces as possible) are placed in each cylinder and the machine is revolved 10,000 times at 30-33 revolutions per minute. The stones should pass through a $2\frac{1}{4}$-inch ring, and be retained on a 2-inch ring. After test the material which will pass a $\frac{1}{16}$-inch mesh sieve is expressed as a percentage of the 11 lbs.

$$\text{French coefficient of wear} = \frac{40}{\text{Percentage of wear}}.$$

A wet test is made by placing 11 lbs. of water with the stone. Usually there is more wear in the wet test than in the dry test.

Effect of Various Factors.—In a Paper [36] read at a meeting of the *American Society for Testing Materials*, S. Walker states : " The studies [37] which have been carried out have generally failed to indicate any definite relationship between the resistance to abrasion of an aggregate and the compressive strength of concrete." From the effect of different

variables in making the test it would also seem that the resistance to abrasion disclosed by the test has no very definite relation to the density of the specimen tested. Concerning this the Paper says : " Probably the relationship is so complicated by the varying combinations of impact and abrasion in the test that it will be difficult to establish."

The variations studied were : (1) Effect of number of revolutions of the cylinder in which the samples were tested ; (2) effect of the weight of the sample taken ; (3) effect of the number of cast-iron balls added as an abrasive charge ; (4) effect of the grading of the sample ; (5) effect of the shape of the pieces tested. Discussing the first of these variations, it was shown that the number of revolutions and the wear have a " straight-line relationship " for hard materials. For softer materials the plot is a decided curve, showing the cushioning effect of the fine particles and dust produced.

The effect of the weight of the sample is shown to be very pronounced. For the three aggregates tested, gravel, limestone and slag, the percentage of wear varied from 14 per cent. to 25 per cent. with a 2,000-gramme sample, while with a 7,000-gramme sample it varied only from 4·7 per cent. to 5·7 per cent. In other words, the large sample showed not only less wear, but much less difference in wear as between different aggregates. The Paper raises the question as to whether the 5,000-gramme sample used in the standard Deval test is too large.

The effect of the number of balls used was shown to be similar to the effect of the number of revolutions.

The effect of the grading of the sample is the most important of all, to judge by the figures and the diagrams in the Paper. The percentage of wear was increased from 1·5 per cent. to 7·5 per cent. by increasing the fines in gravel from zero to 50 per cent., and a similar relationship was established with crushed limestone. Fifty-seven different gradings were tested and plotted, and it was shown that the same percentage of wear could be obtained from many gradings. Just what makes grading so affect the percentage of wear has not been determined, but the

Paper notes that the curves indicating the percentages of wear are similar to those indicating percentage of voids.

Regarding the shape of the pieces tested, it was shown that the wear is less after the angular portions have been removed.

The Paper draws several interesting conclusions regarding the Deval test, but it does not point out any methods by which the standard test used on stone or the Rea modification used on gravel may be particularly improved.

Dorry Abrasion Test.—The Dorry machine [38] consists of a revolving disc on which is fed, at a uniform rate, a standard quartz sand passing a 30- and retained on a 40-mesh sieve. The specimen of stone is prepared in the form of a cylinder 1 inch in diameter and 1 inch long. It is held with its axis vertical, and its lower end pressed with a force of 3·5 lbs. per square inch against the surface of the disc. After 1,000 revolutions at about 28 per minute, the loss of weight of the specimen is determined. The test is repeated with the specimen reversed, and the average loss is used in determining the hardness.

If W = average loss in grammes, then

$$\text{Hardness} = 20 - \frac{W}{3}.$$

Test Values.—These are given in the following table :—

Class.	Attrition Test, per cent. of Wear.		Abrasion Test, Coefficient of Wear.
	Dry.	Wet.	
Very good,	2 & under	2 & under	19 & over
Good,	2·1–2·5	2·1–3·1	17–18·9
Fairly good,	2·6–3·1	3·2–4·0	16–16·9
Rather poor,	3·2–4·0	4·1–5·0	15–15·9
Poor,	over 4·0	over 5·0	under 15

Gravel.

Modified Attrition Tests for Gravel.—In an attempt to get a suitable attrition test for gravel, several experimenters have suggested various modifications, and the more important ones are the following :—

(1) *Lewis Method.*—2,000 grammes of $\frac{3}{8}''$ to $\frac{3}{4}''$ material and 2,000 grammes of $\frac{3}{4}''$ to $1\frac{1}{2}''$ material are placed in the Deval machine with an abrasive charge of ten $1\frac{7}{8}''$ cast-iron balls, 2,000 revolutions being employed.

(2) *Rea Method.*—2,500 grammes of $\frac{3}{8}''$ to $\frac{3}{4}''$ material and 2,500 grammes of $\frac{3}{4}''$ to $1\frac{1}{2}''$ material used. Abrasive charge, six $1\frac{7}{8}''$ cast-iron balls. 10,000 revolutions.

(3) *Mattimore Method.*—Same as standard method, but cylinder slotted to allow dust to escape.

(4) The *American Association of State Highway Officials* adopted the " Rea method " in 1917, and in 1920 revised the specification for grading so as to require 1,250 grammes of each of the following sizes : $\frac{1}{2}''$ to $\frac{3}{4}''$, $\frac{3}{4}''$ to 1'', 1'' to $1\frac{1}{2}''$, $1\frac{1}{2}''$ to 2''.

This method of test has several objections [39] :—(1) The test cannot be made on a gravel unless the necessary sizes are available. (2) When gravel contains a high proportion of material finer than $\frac{1}{2}$ inch, the test sample is not representative. (3) Where the sample contains a considerable quantity of crushed particles the results are not comparable on the same basis as for samples containing no crushed particles. A new method of test has therefore been proposed by the *American Concrete Institute*, and experiments have been started on the lines indicated in the following :

Proposed A.C.I. Test.[40]

" **Test for Gravel containing No Crushed Pieces.**—(1) The sample shall consist entirely of uncrushed fragments of gravel, and the test shall be made using one of the four gradings given in paragraph (3). The grading most nearly representing that of the material furnished for the work shall be selected for the test.

"(2) The aggregate shall first be screened into the different sizes required for the test, and the material of these sizes shall be washed and dried.

"(3) The sample shall consist of 5,000 grammes of the dry gravel, with the different sizes combined to conform to one of the following four gradings :—

Grading.	Size of Screens (Circular Openings).		Percentage.
	Retained.	Passing.	
	inch	inch	
A	½	¾	25
	¾	1	25
	1	1½	25
	1½	2	25
B	½	¾	25
	¾	1	25
	1	1½	50
C	½	¾	50
	¾	1	50
D	¼	½	50
	½	¾	50

"(4) The sample for the test shall be placed in the cast-iron cylinder of the Deval abrasion testing machine as specified for the standard abrasion test for stone.[41] Six cast-iron spheres 1·875 inches in diameter and weighing approximately 0·95 lb. each shall be placed in the cylinder as an abrasive charge.

"(5) The duration of the test and the rate of rotation shall be the same as specified for the standard test for stone, namely, 10,000 revolutions at a rate of 30 to 33 revolutions per minute. At the completion of the test the material shall be taken out and screened over a No. 12 mesh sieve, conforming to the requirements of the Standard Specifications for Sieves for Testing Purposes of the *American Society for Testing Materials* (Serial Designation : E. 11-26). The material retained upon the sieve shall be washed, dried and weighed. The difference between this weight and the

weight of the original sample, expressed as a percentage of the original weight, shall be considered as the loss by abrasion.

"(6) When the gravel has a specific gravity below 2·20, a sample of 4,000 grammes, instead of 5,000 grammes, shall be used for the test. The testing procedure shall be the same in all other respects.

"(7) When the gravel, as used in the work, contains as much as 15 per cent. of material finer than $\frac{1}{2}$ inch, but is of such size that either Grading A, B or C would be used for the abrasion test, a second abrasion test shall be made using Grading D, if, in the opinion of the engineer, the particles finer than $\frac{1}{2}$ inch are not at least equal in hardness to those coarser than $\frac{1}{2}$ inch.

"**Test for Gravel containing Crushed Pieces.**—(8) Gravel containing more than about 15 per cent. of crushed pieces shall, for the purpose of this test, be considered as crushed gravel. In such cases, the abrasion test shall be made on a representative sample of the whole, including the crushed pieces, following the procedure in paragraphs (1) to (7). The percentage by weight of crushed pieces shall be determined, and the permissible percentage of wear which shall govern for any given sample shall be calculated from the following formula :

$$W = \frac{A\,L + (100 - A)\,L'}{100}$$

in which A = per cent. of uncrushed pieces.
$100 - A$ = per cent. of crushed pieces.
L = maximum percentage of wear permitted by the specifications for gravel containing no crushed pieces.
L' = maximum percentage of wear permitted by the specifications for gravel consisting entirely of crushed pieces.
W = permissible percentage of wear.

"It should be recognised that the different gradings of

sample will require the statement of different limiting percentages of wear."

Comparison of Attrition Results.

It was reported [42] a few years ago that in comparing results secured from rock and gravel attrition tests a very unexpected relation was presented. It has been stated that the general assumption regarding the relation between the percentages of wear for the attrition tests on rock and gravel is 1 to 3. The tests reported show that when a given material of uniform composition is tested by both the rock and gravel attrition methods the ratio of 1 to 3 is found to be the exception rather than the rule, and that the average ratio as determined by these tests is 1 to 0·86. In other words, with the materials used, the loss in the gravel test is only 86 per cent. of that in the rock test.

It should be noted that the materials used in these tests were of uniform composition. The results therefore are applicable only to such materials. The average natural gravel, especially that of glacial origin, is not of uniform composition, and the relation found by the foregoing tests cannot be applied to tests on this type of gravel. The non-uniformity in the average gravel emphasises a fundamental weakness in the gravel attrition test and raises a question as to the suitability of such a test. The percentage of extremely soft fragments may prove to be the essential feature in the selection of a gravel for concrete.

CONCRETE.

Abrams states that the quality [43] of the fine or coarse aggregate produces less effect on wear than is commonly supposed. The wearing resistance of concrete is determined largely by the quality of the concrete itself rather than by the type of aggregate. Good concrete can be produced from aggregates which are generally considered inferior, if other factors are taken properly into account.

Even so, where there is severe wear, as in factory buildings,

on railroad platforms, and on pavements, a hard, tough, aggregate is desirable.

Wear Tests on Concrete.—Tests have been made at *Kansas State Agricultural College* to determine the wear on concrete. Three concrete spheres, 9 inches in diameter, were tested in a "rattler," with an abrasive charge of three hundred pounds of cast-iron shot. The following conclusions were reported [44] :—

(1) That the testing of three 9-inch spheres of 60-day concrete in a paving brick "rattler" with a standard abrasive charge is a satisfactory and convenient method of measuring the resistance to abrasion.

(2) That the French coefficient of the coarse aggregate does not materially affect the resistance to wear or the strength of Portland cement concrete of a 1 : 2 : $3\frac{1}{2}$ mix by dry loose volume ; that is, good results may be obtained by the use of any coarse aggregate which is structurally sound.

(3) That different brands of cement produce concretes of different wearing quality.

(4) That the use of a surface hardener will increase the resistance to wear of all concrete, but will affect some brands of cement more than others.

(5) That proper curing is absolutely necessary to produce concrete which will have a high resistance to wear.

(6) That the use of an excessive amount of mixing water will reduce the resistance to wear of concrete in about the same proportion as it will reduce the strength.

(7) That the relation of the wear and strength of concrete is expressed by

$$S = \frac{K}{W^a}$$

in which S = compressive strength in pounds per square inch, W = wear in inches, and K and a (an exponent) are constants.

(8) That "*Lumnite*" cement concrete, of the same proportions as Portland cement concrete, will have the same resistance to wear at 48 hours as the Portland will have at 60 days.

Conclusion.

Although there is still much to be learned concerning the wear of concrete, it seems to be universally agreed that the wear of the aggregate, as demonstrated by the attrition test, is not necessarily a measure of the wear of the concrete made with that aggregate. Further the rigid requirements so often called for when building a concrete road surface may be relaxed safely in many instances without fear; and a lowering of the standard for stone will automatically bring a larger number of quarries into the market, with a resulting reduction in cost to the builder.

CHAPTER VI.

MISCELLANEOUS PROPERTIES OF AGGREGATES.

Cleanness.

A sand which is absolutely clean is difficult to obtain, except in a few favoured localities, and a specification should have a certain tolerance in this respect. Impurities which are frequently present may be divided into

(1) Organic matter,
(2) Fine material, variously called dust, dirt, silt, clay, etc.

Organic Matter.—In parts of the country where trees are plentiful, the sand deposits may become laden with decaying humus. Leaves, etc. form tannic acid on decomposing, and this acid gets into the sand. Again, the careless digging of sand in a pit may cause the top layer, containing vegetable matter, to be included.

It has been found that organic materials retard or prevent the setting and hardening of concrete, so that their presence in the aggregate is a matter of considerable moment. A simple qualitative test has been devised to deal with these organic impurities, and it is known as the "Colorimetric Test."

Colorimetric Test.—Some of the sand to be tested should be placed in a suitable vessel which has been divided into 15 equal parts. The sand should occupy 9 parts and a solution of sodium hydroxide should then be added up to the mark indicating 14 parts. The sodium hydroxide should be a 3 per cent. solution, which may be obtained from any chemist. An approximate method of making the solution is to dissolve 1 oz. of caustic soda in 1½ pints of distilled water. The solution should be used with care, as it will burn hands, clothing, etc. The mixture should be shaken thoroughly and allowed to stand for 24 hours. At the end of this period the presence of organic matter

will be indicated by a darkening of the solution. A tint lighter than straw colour indicates little or no organic matter, but a dark colour suggests that the organic matter is high and the sand should not be used without further investigation. [illegible]crete, [illegible] presence of organic matter delays the initial [illegible] of [illegible] of cement, sand containing this material may be satisfactory in some cases, and it is not suggested that a sand which will not pass the colorimetric test should therefore be condemned on that account.

Limitations of Test.—Occasionally one will find [45] mineral salts in sands which act either detrimentally or as an accelerator, and these substances will not show up with the caustic soda solution. This causes the test to fail in its ultimate purpose, and reliance must be placed upon other physical tests. For this reason, if for no other, over-confidence in the colorimetric test must be avoided.

An important point not to be overlooked, however, is the peculiarity of the district from which a sand comes. Large areas are sometimes supplied with materials which, if use depended upon the indications of organic matter, would never build concrete roads. There are many sands of good quality showing a dark colorimetric test. On the other hand, there are regions in which a testing engineer can safely prophesy the tensile strength ratio by reference to mechanical analysis and colour. Other engineers never find organic matter in their sand even though they experience the usual difficulties with the strength. Thus, the dependability of the test is best judged by those who use it, according to the circumstances involved.

The greatest value of this test is felt by the prospector who is searching in new territory or examining unfamiliar materials. Then, with the aid of a few observations about the source of supply, such as whether the sand is a pit or a river material, the amount and character of overburden or the location of stream and character of pollution, this information, with the organic matter test as a check, would form a sound basis for preliminary reports, provided the size and quality of the sand grains appeared satisfactory.

Excellent use may also be made of the test in the control of materials on the job or at the source of supply. If the

organic matter test means anything whatsoever in the particular instance, it could be made to check up such details of production as stripping and washing. A darkening in colour would indicate that organic matter was increasing, and that materials and operations should be investigated.

In general, it can be said that the colorimetric test for organic impurities as made at present on concrete sands gives only an indication of where trouble might be expected and, as intimated already, should not be used as a positive factor in judging sands except in those localities where experience has shown it to be of undoubted reliability.

Clay.—Numerous tests have been reported during the last 30 years regarding the effect of clay, silt, etc. in concrete. Unfortunately the results appear to be antagonistic in many cases, and there seems little doubt that we shall not be able to be at all dogmatic on the question until a comprehensive investigation has been undertaken. The following conclusions are based on an investigation carried out recently.

It is concluded that in general the presence of clay in sands [46] used for Portland cement mortar is harmful. Sand containing up to 2 per cent. of clean clay, free from organic impurities, may be used with Portland cement for mortar or concrete, provided that laboratory tests are satisfactory. Laboratory tests on argillaceous sand to determine the effect of organic substances which may be present require several months. The effect of clay varies with its condition. Sands containing clay should not be dried before testing, as this leads to exaggerated values for the strength of mortars made with them. The effect of clay varies also with the methods of testing. Tensile tests give a higher limit for clay content than do compressive strength tests, and no conclusions should be drawn from the results of tensile tests alone. The results of determinations of the weight per unit volume of mortars, with and without additions of clay, show that greater weight per unit volume is not necessarily accompanied by greater strength. It is thought that Grün's theory that clay colloids produced by prolonged action of the atmosphere on clay have an unfavourable effect on the processes of crystallisation involved in the setting of cement requires further study.

Test for Clay.—A simple test for clay, etc., is to note the amount of sediment above the sand in the colorimetric test. If the height of this sediment is more than 7 per cent. of the height of the sand, the sand should be viewed with suspicion. It is almost certain that an improvement will be effected by washing.

Even a very small proportion of clay can spoil concrete when it occurs as a fine coating around the pieces of large aggregate, as in many gravels. In such instances it will be found that, on crushing, the pebbles pull out quite easily from the matrix and leave a perfectly smooth bed, indicating that the cement had been unable to grip the pebble on account of the film of foreign matter. In the writer's experience this trouble has been in evidence on many occasions where pile heads have shattered due to this lack of adhesion.

Mica.—The effect of mica [47] in screenings from stone of a micaceous nature has been the subject of considerable controversy. Tests by Feret indicated that the presence of 2 per cent. of mica has but slight influence upon the tensile strength of mortar, but a greater effect upon the compressive strength. More recent tests by Willis [48] in 1907 on mortars made with standard Ottawa sand into which mica was introduced showed that the presence of the mica increased the voids and decreased the strength. The sand used in the tests, loosely shaken, contained 37 per cent. of voids, but as the mica was added the voids increased rapidly until with 20 per cent. mica they were 67 per cent., with a corresponding decrease in weight, and three times the amount of water was required for mixing.

It is thus evident that the reduction in strength was largely due to the decrease in density, and not entirely caused by the slippery character of the grains. In crushed stone screenings it is probable that the effect of the same percentage of mica in the natural state would be less marked.

Black mica, which has a different crystalline form, is not injurious to mortar.

Removal of Debris.—In one instance contractors encountered [49] a difficult problem in trying to screen out the vast amount of small sticks and debris in the sand and

gravel. A large portion of the sticks had a specific gravity slightly greater than 1, and so could not be floated or screened out. Finally, air blowers were suggested as a possible solution of the problem and were tried with entirely satisfactory results. The specific gravity of the foreign matter being about 1 and that of the gravel about 2·7, it was a simple matter to allow the gravel to drop past in a thin sheet and regulate the blowers to remove the debris. Excess water in the gravel was also blown off; this was of some value, as after inundating the sand on this job, it was necessary to draw off as much as 0·5 to 1·7 cubic feet of water, depending upon the grading of the sand.

Dust-Coated Stone.—In 1929, a series of tests [50] was run to determine the effect of dust-coated stone on the strength and other properties of concrete, and during 1930 the one-year strength tests fell due. The previous investigations made at the end of 28 days and 3 months showed that even badly dust-coated stone, provided the coating was entirely of stone dust, did no particular harm to the concrete. The strength of the concrete containing even as high as 5·7 per cent. of stone dust was not materially lowered below that of the concrete in which the stone contained no dust. The percentage of reduction in either beam strength or compressive strength did not exceed 1½ per cent. for each per cent. of stone dust added. Moreover, the wearing qualities of the concrete containing stone dust did not seem to be impaired.

The one-year tests fully bore out the results of the previous tests made at 28 days and 3 months, and for all practical purposes the concrete made with stone having 5·7 per cent. of dust was just as strong as that containing no dust. This investigation should be extended to a wide variety of rocks, for there may be exceptions to the foregoing results.

Weight.

Voids.—The voids in sand, stone, etc., depend on various conditions, as mentioned later, but the following table may be used as an approximate guide:—

Voids in Aggregates.		
Aggregate.	Solids.	Voids.
Sand, moist, fine, passing 18-mesh sieve, . .	0·57	0·43
Sand, moist, coarse, not passing 18-inch sieve, .	0·65	0·35
Sand, moist, coarse and fine mixed, ordinary, .	0·62	0·38
Sand, dry, coarse and fine mixed, . . .	0·70	0·30
Stone screenings and stone dust, . . .	0·58	0·42
Ballast, ¾″ and under, 6 per cent. coarse sand, .	0·67	0·33
Broken stone, 1″ and under, ...	0·54	0·46
Broken stone, 2½″ and under, dust only screened out, ...	0·59	0·41
Broken stone, 2″ and under, most small stones screened out, ...	0·55	0·45

More detailed information is given in the table below,[51] which gives the percentages of voids corresponding to different weights per cubic foot of dry broken stone of various specific gravities.

Voids in Broken Stone.				
Weight of 1 cub. ft. of dry broken stone, lbs.	Percentages of Absolute Voids.			
	Sandstone. Sp. gr. 2·4.	Limestone. Sp. gr. 2·6.	Granite. Sp. gr. 2·7.	Trap. Sp. gr. 2·9.
70	53·2	56·8	58·4	61·3
75	49·8	53·7	55·4	58·5
80	46·5	50·6	52·4	55·7
85	43·2	47·5	49·5	53·0
90	39·8	44·5	46·5	50·2
95	36·5	41·4	43·5	47·4
100	33·1	38·3	40·6	44·7
105	29·8	35·2	37·6	41·9
110	26·4	32·1	34·6	39·1
115	23·1	29·0	31·6	36·4
120	19·8	25·9	28·7	33·6
125	16·4	22·8	25·7	30·8
130	13·1	19·8	22·7	28·1
135	9·7	16·7	19·7	25·3
140	6·4	13·6	16·8	22·5

Determination of Voids.—The following method of determining the voids in coarse aggregate is adopted from an article by C. L. Bourne, in "*Concrete Highway*," July, 1917 :—

Apparatus : Any convenient receptacle of uniform cross-section from top to bottom, also a common rule.

Method : Measure total depth of receptacle and designate by D.

Fill receptacle about half full of water, measure depth of water and designate by W.

Place enough aggregate in receptacle to bring water surface exactly level with top. Shake receptacle sideways a few times, allow to settle and obtain depth of the aggregate ; designate by H.

Then find percentage of voids by the formula :

$$\text{Per cent. voids} = \frac{W - (D - H)}{H} \times 100.$$

Example : Depth of Receptacle $= 24'' = D$.
Depth of Water $= 12'' = W$.
Depth of Aggregate $= 16'' = H$.

Then—

$$\text{Per cent. voids} = \frac{12 - (24 - 16) \times 100}{16} = 25 \text{ per cent.}$$

Specific Gravity.—Taylor and Thompson [52] have pointed out that the uniformity in the specific gravity of different sands is very convenient for calculation. Different authorities who have tested large quantities of sand have reached almost identical conclusions as to the average specific gravity, and all state that it is practically a constant. A. Hazen gives 2·65, W. B. Fuller, 2·64, R. Feret in France states " one may without appreciable error adopt an average specific gravity of 2·65 for siliceous sands," while E. Chandlot gives limits of 2·60 to 2·68 for sands which are not porous. The specific gravity of calcareous sands averages about 2·69 by absolute determination, or about 2·55 if measured by the total volume of the particles having their pores filled with air.

Gravels also have quite a uniform specific gravity. According to A. E. Schutte, who has tested gravel from more than forty localities in the United States and Canada, an average value is 2·66.

The table below gives average values of various concrete aggregates. In every case the specific gravity is the ratio of the weight of an absolutely solid unit volume of each material to the weight of a unit volume of water.

Specific Gravity of Rocks.		
Material.	Specific Gravity.	Weight of a Solid Cubic Foot of Rock in lbs.
Trap, . . .	2·9	180
Granite, . .	2·7	168
Slate, . . .	2·7	168
Gravel, . .	2·66	165
Sand, . . .	2·65	165
Conglomerate, .	2·6	162
Limestone, . .	2·6	162
Sandstone, . .	2·4	150

The weights of several granites are given in the following table :—

Weight of Granite.		
Name.	Place of Origin.	Lbs. per cu. ft.
Dalkey, ...	Dublin.	169
Hey Tor, ...	Devonshire.	165
Blue Penmaenmawr, . .	Carnarvonshire.	160
Aberdeen Grey, ...	Aberdeenshire.	166
Aberdeen Red, ...	,,	165
Cornish Grey, ...	Cornwall.	167
Cornish Red, ...	,,	164
Standard Grey, ...	Bakke.	167
Bon-Accord Red, ...	Sweden.	168
Labradorite Emerald Pearl, .	Norway.	168
Labradorite Royal Blue, . .	,,	168
Carnation, ...	Sweden.	168
Ruby Red, ...	,,	168

Weight of Broken Stone.—The weight per cubic foot of the stone depends on

(1) The specific gravity of the uncrushed rock.
(2) The grading of the crushed rock.
(3) The degree of compacting.
(4) The moisture content.

Assuming a specific gravity of 2·65, the weight of the solid rock would be 165 lbs. per cubic foot. Using this figure as a basis, the weight per cubic foot of the crushed stone would be :

with 40 per cent. voids, 100 lbs. approximately.
with 45 per cent. voids, 90 lbs. approximately.

The percentage of voids would depend on items (2) and (3) above, *i.e.*, the grading and the degree of compacting.

In view of the foregoing remarks it is clear that the weight per cubic foot of broken stone is a very variable figure. For ordinary purposes, however, where more definite values are not available, the following figures might be adopted :—

Screened broken stone, measured loose—90 lbs. per cu. ft.
Screened broken stone, compacted, as after haulage—100 lbs. per cu. ft.
Crusher-run broken stone, measured loose—100 lbs. per cu. ft.
Crusher broken stone, compacted—110 lbs. per cu. ft.

A further point to consider is the water content, which varies from zero to 3 lbs. per cubic foot.

Grading, Voids and Weights.—The effect of grading of aggregate and sand on voids and weights has been discussed recently by S. Walker,[53] and the following conclusions are of particular interest :—

" (1) For three sizes of sand or gravel, such as used in the tests carried out, the least voids were obtained for a combination of the fine and coarse sizes, with the intermediate size omitted. In general 30 to 40 per cent. of the finer size gave the least voids.

"(2) Combinations of two adjacent sizes, that is, fine and medium or medium and coarse, showed relatively small changes in void content for the different proportions. However, as in the case of the fine and coarse, a combination of adjacent sizes containing 30 to 40 per cent. of the finer size had a lower void content than other combinations of two adjacent sizes.

"(3) The general observation may be made that, for the sizes used in the tests carried out, the void content of any size was reduced by the addition of a finer size up to about 40 per cent. or of a coarser size up to about 60 per cent.

"(4) There was an approximately constant difference between the voids as determined by the loose or rodded method. In the case of gravel this difference was 3 to 4 per cent., and in the case of sand it was 5 to 7 per cent.

"(5) For quantities of sand greater than required to produce minimum voids, the mixtures containing the coarser sand produced the lower void contents.

"(6) The coarser sands used in this investigation had lower void contents than the finer ones.

"(7) For gravel as the coarse aggregate the same percentage of sand produced minimum voids, regardless of the grading of the sand; the minimum voids obtained with a given grading of gravel was the same for the different gradings of sand.

"(8) For granite as the coarse aggregate, the percentage of sand required to produce minimum voids varied as the grading of the sand varied; there is, however, no indication of a definite relationship.

"(9) The percentage of minimum voids for each combination varied with the grading of the coarse aggregate. The larger-sized coarse aggregates gave the lowet void contents for mixtures of sand and coarse aggregate. This relationship seems to be a function of size of particle and, probably, of size of void spaces, rather than percentage of voids in the coarse aggregate.

"(10) Sands increase in bulk when moist. The amount of bulking depends upon the percentage of moisture and the method of measurement. Bulking is accompanied by an increase in the percentage of voids.

"(11) Maximum bulking is obtained with 3 to 10 per cent. moisture, depending on the grading of the sand. Finer sands require more moisture to produce maximum bulking than do coarse sands.

"(12) Fine sands bulk more than coarse sands. For the usual conditions (3 to 6 per cent. moisture), 20 to 45 per cent. bulking may be expected, depending on the grading of the sand and the method of measurement.

"(13) Bulking is not a factor in the measurement of sand by weight. Weight measurements, however, should take into account the weight of water present at the time of weighing.

"(14) Inundation minimizes the bulking of moist sand and gives a value approximately equal to that of the sand measured in a dry and loose condition."

MISCELLANEOUS.

Flat Pieces.—Many specifications for coarse aggregates [54] require that there shall be not more than 5 per cent. of flat and elongated fragments when the aggregate is to be used in concrete. The definition of "flat and elongated fragments" differs in various localities. In some States of U.S.A. a "flat piece" is defined as one whose least dimension is one-fifth of its greatest dimension, and in other States "flat pieces" are those in which the least dimension is one-half of the greatest dimension. This very difference in definition shows a great variation in engineering opinion, and illustrates forcibly a lack of knowledge as to what does constitute "flat fragments."

The general conclusions resulting from research work carried out by the *National Crushed Stone Association* in the United States of America are as follows:—

(1) Flat and elongated pieces, to a small extent, increase the percentage of voids in the stone aggregate, and probably to a slight extent decrease the workability of the concrete, because of the resulting decrease in the ratio of volume of mortar to volume of voids in the stone. However, a considerably greater increase in voids takes place due to

variations in gradation, which may produce much harsher workability than produced by flat and elongated pieces.

(2) Flat pieces up to 10 per cent. in the 1 : 2 : 4 mixtures, and 15 per cent. in the 1 : 2 : 3½ mixtures, do not decrease the strength of the concrete.

(3) The indications are that the flat pieces do not lie in a position such as to cause trouble on the surface of a concrete slab.

Moisture in Aggregates.—Fine aggregates [55] practically always contain moisture and, therefore, it will not be necessary, ordinarily, to determine their absorption. The determination of absorption by fine aggregates is somewhat difficult, and methods for carrying it out are not well standardised. If the information is required, it should be obtained by a competent operator in a well organised laboratory. The absorption by coarse aggregates can readily be determined by anyone with simple equipment available. The determination consists merely of immersing a weighed sample of the dried aggregate in water, allowing it to remain immersed for a specified period, then removing it, carefully surface-drying it with a towel, and determining the gain in weight. The value of absorption after a period of 30 minutes is recommended as being most suitable for calculation purposes.

Tests have been carried out [56] on some 30 limestones and dolomites, having absorption ratios (calculated by the A.S.T.M. method, 24-hour immersion) ranging from 0·1 to 8·8 per cent. by weight. Porous aggregate takes up from 50 per cent. to 75 per cent. of its total absorption capacity in 20 minutes or less, and, with the more porous types, absorption is complete in half that time. It seems, therefore, that porous aggregates absorb their total capacity of the mixing water during the time of mixing and the next few minutes in the conveyor, chute or forms. It is concluded that, in normal circumstances, a porous aggregate in a wet mix absorbs almost, if not quite, its full capacity of water before the concrete sets, and that, therefore, the amount of mixing water is considerably reduced before the setting process commences and the consistency of the mix thereby affected.

Tests.—It often happens that peculiarly small samples of stone and sand are submitted to laboratories for examination and it should be realised that tests can only be carried out properly when sufficient material is sent. The tests most frequently required are those for general suitability and compression (when used in concrete), and the following quantities should prove adequate :

Tests for general suitability, . .	7 lbs.
Compression tests, . . .	56 lbs.
Fuller compression tests, . .	1 cwt.
Long period tests, ...	2 cwt.

The fees charged at the National Physical Laboratory, Teddington, Middlesex, are £2 2s. 0d. for each of the following tests, or £7 7s. 0d. for all the tests on one material :

1. Abrasion.
2. Absorption and Specific Gravity.
3. Attrition.
4. Cementitious Value.
5. Crushing.
6. Impact.

A summary of tests carried out at the National Physical Laboratory [57] on 129 aggregates is given in the table on page 108.

Soundness Test.—The following details relate to a soundness test for aggregates which has been developed in the United States of America as a result of intensive research by several important laboratories. Acknowledgment is made to the *National Sand and Gravel Bulletin*, from which the notes have been taken.[58]

"*Scope* : 1. This method describes the procedure to be followed in treating fine and coarse aggregates to determine their resistance to disintegration by a saturated solution of sodium sulphate.

"*Equipment* : 2. The equipment for carrying out the test consists of a supply of sodium sulphate solution, containers for immersing the aggregate samples, equipment for weighing the samples and a drying oven.

NATIONAL PHYSICAL LABORATORY TESTS ON STONES.—AVERAGE VALUES FOR EACH GROUP OF STONES.

Trade Name.	Attrition Test, Per cent. Loss of Weight.		Abrasion Test, Coefficient of Hardness.	Impact Test, No. of Blows.	Crushing Stress, lbs. per sq. in.	Absorption of Water, lbs. per cub. ft.	Specific Gravity.
	Dry.	Wet.					
Granite, . .	2·6	2·6	18·7	14	26,000	0·26	2·65
Gabbro, . .	2·8	2·8	18·8	20	30,000	0·32	3·17
Porphyry, . .	2·8	2·4	19·3	19	33,900	0·63	2·65
Andesite, . .	3·0	5·6	18·0	19	21,000	0·17	2·79
Basalt, . .	3·5	6·1	17·3	17	27,200	0·53	2·87
Schist, . .	2·9	3·1	19·1	17	36,400	0·13	2·69
Quartzite, . .	3·2	3·9	18·8	13	36,000	0·47	2·63
Grit, . .	3·0	4·8	18·3	18	31,000	0·49	2·66
Limestone, . .	5·2	9·4	16·4	10	19,400	1·03	2·67
Artificial (slag), .	7·1	7·2	17·0	9	16,500	2·78	2·73

"3. The sodium sulphate solution shall be a saturated solution prepared by dissolving sodium sulphate, either of the anhydrous or crystalline form, in water at a temperature of about 30° C. The solution shall be thoroughly stirred during the addition of the salt and sufficient excess shall be added to ensure saturation (about 0·9 lb. of the anhydrous form or 2·0 lbs. of the crystalline form will be required for each quart of water). The solution shall be allowed to cool to a temperature of $21 \pm 2°$ C. and shall stand at least 12 hours before use.

"4. The containers shall be non-metallic or of enamel-ware and of a size that will allow a depth of at least one-half inch of solution above the immersed sample of aggregate. They shall be equipped with suitable covers to minimize evaporation.

"*Note.*—A convenient size of container for the samples of fine aggregate, described subsequently, is one about 6 inches in diameter (or square) and 1¾ inches deep; for the coarse aggregate samples a container 9 inches in diameter (or square) and 3 inches deep will be found convenient.

"5. For fine aggregate samples a balance having a capacity not less than 1,000 grammes, sensitive to at least 0·5 gramme, is required. For coarse aggregate samples a balance having a capacity not less than 5,000 grammes, sensitive to at least 1 gramme, is required.

"6. The drying oven shall provide a circulation of dry air and shall be capable of maintaining a temperature of 100° to 110° C.

"*Samples*: 7. The sample of fine aggregate passing a ⅜-inch sieve shall be of such size that approximately 500 grammes are coarser than the No. 50 sieve. The sample shall be thoroughly washed and dried to constant weight at 100° to 110° C. and separated into different sizes by screening over standard sieves, numbers 50, 30, 16, 8 and 4. That portion of the sample finer than the No. 50 sieve shall, for the purpose of this test, be discarded. The separated fractions retained between the No. 50 and No. 30 sieves, the No. 30 and No. 16 sieves, the No. 16 and No. 8 sieves, the No. 8 and No. 4 sieves, and coarser than the No. 4 sieve, shall be weighed and placed in separate containers for the test.

"8. The sample of coarse aggregate shall consist of material which has been thoroughly washed and oven-dried to constant weight at 100° to 110° C., and from which the sizes finer than the No. 4 sieve have been removed. Pieces showing incipient fracture due to crushing shall be removed. The weight of the sample shall depend on the maximum size of the aggregate and shall be determined from the following table :—

Weight of Sample to be used for Soundness Test.	
Maximum Size of Aggregate.	Approximate Weight of Sample, Grammes.
$\frac{3}{8}''$, . . .	500
$\frac{3}{4}''$, . . .	1,000
$1\frac{1}{2}''$, . . .	3,000
More than 15 per cent. coarser than $1\frac{1}{2}''$, . . .	4,000

The sample shall be separated into different sizes by screening over sieves having square openings of $\frac{3}{8}''$, $\frac{3}{4}''$ and $1\frac{1}{2}''$. The separate fractions shall be weighed and placed in separate containers for the test. In the case of the fractions coarser than $\frac{3}{4}''$, the number of particles shall be counted.

"*Procedure*: 9. Sufficient of the prepared solution of sodium sulphate shall be added to the fractions of samples in the containers to cover them to a depth of about one-half inch. The containers shall be covered to reduce evaporation and prevent the accidental addition of extraneous substances. The immersed samples shall be stored at a temperature of 21 $\pm$ 2° C. for a period of 18 hours.

"*Note* :—A moist room such as is used for curing concrete test specimens offers a convenient means of controlling the storage temperature.

The presence of a few crystals of sodium sulphate in each container is desirable as an indication that the solution is saturated.

" 10. After the 18-hour immersion period the sodium sulphate solution shall be siphoned or decanted from the container and the samples, in the containers, placed in the drying oven. The oven shall have been previously brought to 100° to 110° C. Care must be exercised to avoid loss of any of the aggregate particles or detritus coarser than 100 mesh. The samples shall be dried to constant weight, or for not less than 4 hours, at the specified temperature. After drying, the samples shall be allowed to cool to room temperature, when they shall again be immersed in the prepared solution as already described.

" 11. The process of alternate immersion and drying shall be repeated until the required number of cycles is obtained. Unless otherwise specified, 5 cycles shall constitute a test.

" *Examination* : 12. Fractions of samples coarser than $\frac{3}{4}$ inch shall be examined qualitatively after each cycle and quantitatively after the completion of the test. Fractions finer than $\frac{3}{4}$ inch shall be examined quantitatively only, and after the completion of the test.

" 13. The qualitative examination and record shall consist of two parts : (1) Observing the effect of action by the sodium sulphate solution and the nature of the action, and (2) counting the number of particles affected.

" *Note* : Two general types of action may be expected : disintegration and splitting. Disintegration is the reduction of a particle into finely divided grains or sludge ; splitting is the separation of the particle into several fragments along natural lines of cleavage.

" The qualitative examinations shall be made with the sample immersed and saturated. That is, the examination for the first cycle shall be made immediately before the sample is removed from the solution for the second drying.

" 14. The quantitative examination shall be made as follows :

" (*a*) After the completion of the final cycle, and after the sample has cooled, the sodium sulphate shall be washed from the sample by means of warm water. This shall be done by covering the sample with fresh, clean warm water and allowing it to remain for at least one hour and repeating this operation at least four times. Fine aggregates

and materials of high absorption may require a greater number of washings.

"(*b*) After the sodium sulphate has been removed, each fraction of the sample shall be dried to constant weight at 100° to 110° C., weighed and screened over the sieve on which it was retained before the test. Particles split into more than two pieces, but which do not pass the sieve opening, shall be considered to pass to the next smaller sieve size. The material passing and considered to have passed the sieve shall be weighed and the weight recorded.

"(*c*) After treating each separate fraction of sample as described in (*b*), all sizes, including the detritus, shall be combined and a sieve analysis made using as many of the following sieves as are required: No. 100, 50, 30, 16, 8, 4, $\frac{3}{8}''$, $\frac{3}{4}''$, $1\frac{1}{2}''$. Those particles which were passed through a sieve by visual examination in paragraph 14 (*b*) shall be passed in this analysis also. The results of the sieve analysis shall be recorded as cumulative per cents. retained on each sieve.

"*Report*: 15. The report shall consist of the following data:

"(*a*) Weight of each fraction of sample before test.

"(*b*) Number of particles in each fraction of sample coarser than $\frac{3}{4}$ inch before test.

"(*c*) Number of pieces affected after each cycle, in fractions coarser than $\frac{3}{4}$ inch only, classified as to number disintegrated and number split.

"(*d*) Material from each fraction of sample finer than sieve on which fraction was retained before test, including failed particles which did not pass, expressed as per cent. by weight of fraction.

"(*e*) Weighted average of per cents. of loss for sample, calculated from results for each fraction.

"(*f*) Sieve analysis and fineness modulus of sample before test.

"(*g*) Sieve analysis and fineness modulus of entire sample after test.

"16. The following tables are convenient forms for tabulating the results:—

QUANTITATIVE EXAMINATION.

Sizes Sieve (Square).	Weight of each Fraction, grammes.			Sieve Analyses.		
	Before Test.	After Test.	Loss Per cent.	Sieve Size.	Per cents. Coarser. Before Test.	Per cents. Coarser. After Test.
No. 50 to 30				100		
No. 30 to 16				50		
No. 16 to 8				30		
No. 8 to 4				16		
No. 4 to $\frac{3}{8}''$				8		
$\frac{3}{8}''$ to $\frac{3}{4}''$				4		
$\frac{3}{4}''$ to $1\frac{1}{2}''$				$\frac{3}{8}''$		
Over $1\frac{1}{2}''$				$\frac{3}{4}''$		
				$1\frac{1}{2}''$		
Average per cent. loss (Weighted)				F.M.		

QUANTITATIVE EXAMINATION.

Made on fractions of sample coarser than $\frac{3}{4}$ inch only.

Cycle No.	Number of Particles. $\frac{3}{4}''$ to $1\frac{1}{2}''$.				Number of Particles. Coarser than $1\frac{1}{2}''$.			
	Before Test.	Disintegrated.	Split.	Unaffected.	Before Test.	Disintegrated.	Split.	Unaffected.
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								

Particular Aggregates.

Broken Concrete.—The use of broken concrete as an aggregate should only be allowed where high strength is not required, and where there is no necessity for watertightness. It might, for instance, be suitable for the bottom course of a floor subjected merely to light traffic, or in foundations to small buildings. Even then, a broken concrete should be used only instead of the coarse aggregate, clean sand being used with it. High strengths could not be expected.

Chert.—Chert is a variety of hornstone resembling flint, but more brittle and having a more splintering fracture.

The effects [59] observed in concrete containing chert aggregate are serious both as to the appearance and the strength of the work. Whenever a piece of chert has a position in the concrete near enough to the surface to be readily subjected to the freezing and thawing action of a winter season, the resulting expansion ends in radiating cracks as well as "spalling" and "pop-outs." The final result is a considerable weakening of the concrete in pavement or structure. If the entire coarse aggregate content of the concrete is the chert mentioned, a sufficient number of cycles of freezing and thawing will result in a virtually complete disintegration of the concrete as rapidly as the progressive disintegration exposes fresh surfaces of the structure to the weathering effects. The presence of small quantities of the chert in the coarse aggregate results in a varying amount of surface effect and strength reduction. The deleterious effect has been verified both by laboratory test and field observation, and action has been taken by the *Missouri Highway Department* limiting the percentage of the objectionable material to 5 per cent. of the coarse aggregate by volume.

Samples of chert [60] obtained by A. A. Anderson, when subjected to freezing and thawing, completely disintegrated after a few cycles. When subjected to the sodium sulphate test the material was sound.

The "powdering" of chert is difficult to explain, but

according to G. P. Merrill, it may be due to the removal of a small percentage of interstitial calcium carbonate, or may even be a change of physical form. E. C. E. Lord has stated that cherts which do stand up, probably do so because of the development of hydrated opaline silica. This silica has a high binding power. He considers that the silica is derived from the solution of part of the rock, followed by deposition. Thus partial decomposition may result in a strengthening of the rock.

H. F. Kriege carried out investigations at the *France Stone Company's Laboratory* upon 100 per cent. chert, cherty limestone (50 per cent. chert) and chert-free limestone, derived from three different sources. Concrete specimens were made and subjected to freezing and thawing, dry thermal expansion (up to 175° C.) and the sodium sulphate test. The same series of tests, except the dry thermal expansion, was carried out on the aggregate alone. The absorption of these aggregates and sodium sulphate observations on a number of cherts are also reported. A chemical analysis of a 100 lbs. chert boulder from the Burlington formation showed good agreement in composition between the chalky exterior, white dense interior, and the translucent centre. Unsoundness of aggregates is considered, and the last paragraph of Kriege's article reads :—" In conclusion, it must be stated that many cherts are unsound or unstable. The two factors which seem to contribute most to the instability of certain cherts are the microscopic irregularities of texture, and the presence of firmly embedded foreign crystals, such as pyrite, with their different physical properties."

Microscopic examination [61] of cherts reveals an irregular structure built up of amorphous, micro-fibrous and micro-granular forms of silica, resulting in a poorly defined, variable texture, which is particularly evident in those cherts which exhibit most marked disintegration in the weathering tests. The sound cherts, on the other hand, show a definite granular texture, and it is stated that in the many specimens examined, this microscopic structural difference has been of great value in predicting soundness. Pyrites is commonly associated with chert, and rapidly oxidises

on exposure, and it is thought that the presence of specular or aggregated pyritic masses within the chert might induce such strains under atmospheric changes as would cause rupture of the chert encasement.

Glass.—An interesting use of waste glass as an aggregate was reported a few years ago. It often happens [62] that a glass tank built of brick and lined with fire tile, breaks open and leaks or burns out with extreme heat. In order to repair the tank the fires must be killed, as the molten glass cannot be drained off. Once the glass has become cold, a solid mass remains that has to be broken up with sledges, bars, picks, etc. As the glass clings to the fire tile, the tile also has to be removed. Inasmuch as a quantity of this material was on hand, and because considerable difficulty would have been experienced in securing other suitable material, it was decided to use the broken glass and fire tile for concrete.

In the concrete, the lumps of glass and fire tile were broken to about $1\frac{1}{2}$ inches in size. The concrete was mixed in the proportion of one part cement, two parts sand, and five parts broken glass and fire tile. The concrete wall had a thickness of 12 inches and was carried to a depth of 9 feet. The footings under the wall were composed of the same material. No reinforcement was used. After the forms were removed it was evident that the concrete used made a very substantial wall.

Minion.—Minion has the appearance of red shale, and is the name given to the refuse from blast furnaces. As it consists of cinders, iron oxide, etc., with apparently no harmful material, it may be used as an aggregate in certain instances.

Sea Sands.—The suitability of sea sands for concrete purposes depends, similarly to the other sands, on their grading and the presence of impurities. Most sea sands are on the fine side, although gradations to coarse gravel and pebbles are found in many localities. The grains usually are rounded, and consequently help to give a good working consistency with a small water content, provided the sand is coarse enough.

The presence of salt usually is not detrimental, except

perhaps in ornamental work, where efflorescence may be troublesome. This usually is only of a temporary character, and the salt being soluble is easily removed. Organic matter may, however, be present in quantities sufficient to cause slow hardening. This should always be tested for, before using an unwashed sand of any derivation. Chalk and shells may be present, but usually quartz predominates. Speaking generally, sea sands, if carefully selected, with due regard to grading and absence of impurities (particularly organic matter, and in a minor degree chalk or other soft material), should prove satisfactory for general concrete work. For high-class reinforced concrete construction samples should be submitted for expert opinion.

The sand preferably should be taken from above or below the tide water, as otherwise it is likely to contain organic and other deleterious matter. Further, sand above high-water mark contains a comparatively high proportion of salt, owing to successive evaporations of spray. Assuming that the sand is dredged from below low-water mark, there will be very little salt present. Ordinarily, sand may contain about 3 per cent. of water, and as sea water contains on an average 2 per cent. of salt, the salt content of the sand would be 0·06 per cent., which is negligible.

It cannot be overlooked that thousands of tons of beach sand and shingle have been used in concrete structures without any trouble arising.

Shaley Gravel.—Shale certainly is harmful to the strength of concrete, but for particular purposes the quantity present may not be great enough to justify the condemning of the gravel. If the work is important, a fully representative sample of the gravel should be sent to a qualified tester for a report. The following conclusions, drawn by F. C. Lang from his tests on gravels containing shale, were reported in 1927 [63] :—

" (1) The presence of shale, even in small quantities, is very detrimental to the strength of concrete, especially when the concrete is used in structures where it will be subjected to an alternate freezing and thawing action.

"(2) The strength of concrete containing shale varies inversely with the percentage of shale the coarse aggregate contains.

"(3) The effect of weathering on shale is shown in the decreased strengths where test specimens were subjected to freezing and thawing. When the coarse aggregate contained more than 60 per cent. shale, the strength was very low, and the freezing and thawing did not appear to weaken it further.

"(4) Concrete in which the coarse aggregate was 100 per cent. shale showed a compressive strength in twenty-eight days equal to about 40 per cent. of the strength of concrete which contained no shale. It is probable that eventually such concrete would entirely disintegrate.

"(5) In these tests care was taken to see that there was no separation of the shale due to its lighter weight. This care could not be taken in ordinary construction, especially of pavements."

Shingle.—Shingle (or ballast) is quite satisfactory for use in concrete if it is clean and suitably graded. The supply should be tested for fine material, and if this is excessive, it should be washed. The larger stones should be screened out, and if, after crushing, the broken stone is recombined with the smaller sizes, a very serviceable aggregate should be obtained.

Spar.—Aggregates containing certain zinc compounds confer very slow-setting properties upon the concrete. The instance of a concrete floor made from mine chippings and cement in the proportions of 4 : 1, which did not show any signs of setting in 7 days, was the original cause of the investigation which led to the above conclusion. Some of the chippings were examined in the laboratory,[64] and the non-setting was proved definitely to be a property of this material. Analysis showed the chippings to consist of about 75 per cent. silica, together with compounds of lead, calcium, zinc and magnesium. The lead would almost certainly be present as sulphide, but the zinc might be present as sulphide, oxide or carbonate. The trouble obviously lay in the presence of one of these unusual substances, so in order to determine which, the problem was

attacked by making concrete and adding definite quantities of lead sulphide, zinc sulphide, zinc oxide and zinc carbonate to the mix. The table below gives a summary of the results of the experiments, and shows that zinc in the form of oxide or carbonate is responsible for the slow setting.

Effect of Adulterants on Strength of Concrete.

Materials Added to the Extent of 3 per cent. on weight of Cement.	Strength of Concrete expressed as per cent. of Strength of Similar Concrete containing No Adulterants.				
	7 Days.	28 Days.	3 Mths.	6 Mths.	12 Mths.
Lead sulphide,	87	111	96	99	111
Zinc sulphide, .	103	102	97	95	10[illegible]
Zinc oxide, .	14	69	75	68	6
Zinc carbonate,	Not done	12	42	76	

Trent gravel, sand and cement were used proportions of 4 : 2 : 1. The 3 per cent. on the the cement represents 0·46 per cent. on the grave[illegible]

The two samples of mine chippings were th[illegible] comparison with similarly-graded granite chi following results :—

Tests on Mine Chippings.

Sample.	Per cent. Zinc Carbonate.	Strength of Concrete exp Strength when using Similai	
		7 Days.	28 Days.
No. 1, .	3·8	0	2
No. 2, .	0·08	5	90

These tests were made on concrete, using the chippings as received and cement in the proportions of 4 : 1.

The results of the tests indicated that if the zinc-bearing concrete is kept wet, it can be expected to reach a satisfactory strength. Further tests on small pats showed that, apart from the slowing of the set, the real danger lay in allowing the mixing water to evaporate before the set could commence, since, when that happened, the concrete was permanently ruined.

Many opportunities have occurred for examining aggregates containing zinc compounds, sent for examination 'ecause concrete made from them would not set, and, in ıost cases, the recommended procedure of keeping the ncrete wet has saved it from having to be pulled up and aid.

tone Sand.—The possibility of using stone sand as a fine ·egate in concrete is becoming of increasing interest to producers of crushed stone, for many of them have amounts of fine material piled up for which they do em to have developed a suitable market. There are ·s in which stone sand has been used with remarkable It seems to have the property of imparting inarily high transverse strength to concrete, and property which is most desirable for concrete construction. The preparation of stone sand is ·e process, and consequently the material cannot ɔete successfully with natural sands.

·m of the optimum gradation of stone sand e solved and, moreover, the use of stone coarse aggregate in a way such as to produce ·ete requires solution. It would be desirable be found for using stone screenings as fine ncrete so that not too much preparation ıry, except to ensure the cleanliness of the anliness in this instance is meant freedom rious substances, which may not include

have been made on the proper gradation ore investigations are needed to confirm btained.

SPECIFICATIONS.

An engineer will be able to construct his own specifications for aggregates from the information given in this and the three preceding chapters, when the points discussed are considered in relation to his particular requirements. It should be realised that there is still considerable difference of opinion regarding these specifications, so that it is impossible to lay down hard and fast rules. However, as a guide, the following specifications have been adopted by the writer for aggregates used in the construction of concrete roads.

Fine Aggregate.—Fine aggregate shall consist of natural sand, stone screenings, or other inert materials with similar characteristics, or a combination thereof, having clean, hard, strong, durable, uncoated grains. When incorporated in the pavement mixture, fine aggregate shall be free from frost, frozen lumps, injurious amounts of dust, mica, soft or flaky particles, shale, alkali, organic matter, loam, or other deleterious substances. 95 per cent. of the fine aggregate, when dry, shall pass a $\frac{3}{16}$-inch screen ; not more than 25 per cent. shall pass a 50-mesh sieve, and not more than 10 per cent. by weight shall pass a 180-mesh sieve. In no case shall fine aggregate be accepted containing more than 3 per cent. by dry weight, nor more than 5 per cent. by dry volume, nor more than 7 per cent. by wet volume, of clay, loam, or silt. If any sample of fine aggregate shows more than 7 per cent. of clay, loam or silt in one hour's settlement after shaking in an excess of water, the material represented by the sample will be rejected.

Coarse Aggregate for Bottom Course.—Structurally-sound material considered too soft for a pavement surface may be used as the coarse aggregate in the bottom course. It shall consist of crushed rock, pebbles (gravel), or other material approved by the engineer. The particles of coarse aggregate shall be of clean, durable material, free from

injurious amounts of vegetable or other deleterious substances, and shall contain no flat or elongated pieces.

(*Note*: It may be necessary to specify the sizes, grading and quality of coarse aggregate in accordance with local conditions. In every case, the engineer should provide specifications which will require the use of the best coarse aggregate which is economically available. These items covering size and grading of coarse aggregate are intended for use with proportions from 1 : 2 : 4 to 1 : 1½ : 3.)

The size of the coarse aggregate shall be such as to pass a 1½-inch mesh. Coarse aggregate shall be uniformly graded within the following limits, and any material which does not come within the limits shall be rejected.

Passing 1½-inch mesh, 100 per cent.
Passing $\frac{3}{16}$-inch sieve, not more than 5 per cent.

Coarse Aggregate for Top Course.—This shall consist of crushed rock, pebbles (gravel), or other material approved by the engineer. The particles of coarse aggregate shall be of clean, hard, tough, durable material, free from injurious amounts of vegetable or other deleterious substances, and shall contain no soft or elongated pieces.

The size of the particles shall be such that at least 95 per cent. pass a ½-inch mesh and not more than 5 per cent. pass a $\frac{3}{16}$-inch sieve, with all the intermediate sizes retained.

Storage.—Aggregates shall be so stored as to avoid the inclusion of foreign materials. Frozen aggregate, or aggregate containing lumps of frozen material, shall be thawed before using.

American Specifications.—The following suggestions were put forward by *Committee C. 9* at the *31st Annual Meeting of the American Society for Testing Materials*, June, 1928.

A new tentative standard [65] for concrete aggregate is included in the report of this committee. This specification proposes maximum limits for deleterious substances in fine aggregate, as follows :—

	Per cent. by Weight.
Removed by decantation,	3
Shale,	1
Coal,	1
Clay lumps,	1
Other local deleterious substances,	—

It is recognised that, under certain conditions, limits lower than those given should be specified.

The proposed grading of sand is as follows :—

	Per cent.
Passing a $\frac{3}{8}$-inch sieve, . .	100
,, No. 4 sieve, . .	85 to 100
,, No. 16 sieve, .	45 to 80
,, No. 50 sieve, .	2 to 30
,, No. 100 sieve, .	0 to 5

It is recognised that these gradings may require to be altered, within the limits given, to suit local conditions. In case the concrete resulting from a mixture of aggregates with extreme limits of grading lacks workability, the use of a fine aggregate having a higher percentage of fine particles, or of a coarse aggregate having a lower percentage of fine particles, is permissible. The mortar strength test of fine aggregate at 7 and 28 days shall not be less than the strength developed under the same conditions by standard Ottawa sand.

Maximum limits for deleterious substances in coarse aggregate are also proposed, as follows :—

	Per cent. by Weight.
Removed by decantation, . .	1
Shale, ...	1
Coal, ...	1
Clay lumps, ...	$\frac{1}{2}$
Soft fragments, ...	5
Other local deleterious substances, .	—

Here it is also recognised that, under certain local conditions, limits lower than those given may be specified. The sum of shale, coal, clay lumps and soft fragments shall not exceed 5 per cent.

A table shows the proposed grading for coarse aggregate, based on the American No. 4 sieve. Blast-furnace slag, meeting the specified grading requirements, shall conform to certain minimum weight requirements, viz., base concrete

65 lbs. per cubic foot, surface concrete subject to abrasion 70 lbs. per cubic foot. Coarse aggregate shall pass a sodium sulphate accelerated test for durability ; aggregates failing in this test may be used provided that they satisfactorily pass a freezing and thawing test. The prescribed methods of sampling and testing are enumerated, and include sieve analysis, decantation test, tests for organic impurities, mortar strength, compressive strength, soundness, freezing and thawing, testing for shale and coal, soft fragments, moisture, consistency, weight of slag and abrasion tests.

CHAPTER VII.

ADMIXTURES.

General.

Admixtures are substances, other than cement, aggregates and water, which are added to concrete mixtures for the purpose of imparting to the latter certain improved qualities. The aim may be to modify the concrete with regard to :—

1. Water-resisting qualities.
2. Strength.
3. Uniformity.
4. Workability.
5. Resistance to wear.
6. Bulk.
7. Resistance to frost.
8. Hardening.
9. Colour.
10. Setting.

There are numerous admixtures on the market, and some of these are particularly good, since they effect an improvement in more than one direction. For instance, a material which improves the workability may allow a drier mix to be used, with resulting increase in strength, etc. Their use is steadily increasing, as those engaged in concrete construction realise their value, and they can often be regarded as an added " factor of safety " for the particular property considered. Care is necessary in the selection of the admixtures, and when used they should be added only in the stipulated quantities. A good admixture may have disastrous results if the quantity is doubled. Many engineers believe that the use of a " foreign " material in the mix must necessarily reduce the ultimate strength

of the concrete. Most of the powdered admixtures do affect the strength, but it has been shown that the small quantities usually used do not detract appreciably from it, except in the case of the rich mixes, when the admixtures are no longer required. This statement refers more particularly to the powdered admixtures used to increase the workability.

The possibilities of admixtures are enormous, and that the importance of this question is realised is evident by the extensive research being carried out in Europe and America. Such a comparatively small amount of information is available, and there are so many materials to consider, that it is natural for experimental results to conflict in some cases.

There are literally hundreds of admixtures on the market, so that choice becomes a matter of extreme difficulty. To complicate matters, an admixture is usually sold under a trade name, and no indication is given of its constitution. This means that the practical buyer is not much better off even if he knows that calcium chloride is good, that washing soda is not to be recommended, etc. A commercial solution may be just the same as a proprietary article selling at double the price. On the other hand, it may look the same, and the same claims may be made for it, but it could be quite different. The following very brief list indicates some of the materials tried for various purposes.

Preservatives.—Tar products, bitumen, calcium chloride, lime, barium oxide, organic oils, mineral oils.

Pore Fillers and Pozzolanas.—Trass, burnt clay, stone meal, brick meal, aluminium sulphate, alum.

Accelerators.—Lyes, calcium chloride, soda, potash.

Anti-freezing Materials.—Calcium chloride, common salt, potassium chloride, potash.

Few admixtures—very few—appear on the market undisguised, and the vast majority have interesting names, and indeterminate chemical compositions. A buyer depends for his facts on the salesman, and in many cases it is only too evident that the information he gets is not what he would really like to have. The admixture which he favours cannot be tested in accordance with any recognised

standards, and it is rarely possible for him to judge whether it will do what is claimed or not.

The question has been dealt with at length by A. R. Lord, in an article entitled "The Fifth Ingredient," which appeared in the January 1930 issue of the *Journal of the American Concrete Institute.* Lord prepared a questionnaire for the suppliers of admixtures, and it is interesting to note his comment that though many were taken from his office only one was returned. With due acknowledgment the questionnaire is reproduced below. It can be assumed that the filling up of this form would effectively take the place of tests—for the present at any rate. It is not suggested that this form is always required. A tried and proved admixture may be accepted without fear, and only the "new comers" need be subjected to a rigorous enquiry.

QUESTIONNAIRE.

Name of Admixture....................................

1. Statement of nature of material: Liquid, powder, premixed with cement at mill, chemical composition (if public). Variation in product of different manufacturers, selling under same trade name. Source of material.

2. Purposes for which used and method of application.

3. Theory of its effectiveness.

4. Cost to produce and to apply.

5. Properties of the material:—
   (*a*) Weight, voids, specific gravity, fineness and gradation.
   (*b*) Moisture carried and bulking effects.
   (*c*) How measured on job.
   (*d*) Chemical reaction on other materials likely to be used with it.
   (*e*) Deterioration due to age or storage.
   (*f*) Cautions (hot water dangers, etc.).
   (*g*) Will it be carried away by percolating water?

6. Effect on properties of concrete (including effect of variation in product of different manufacturers):—
   (*a*) Weight.
   (*b*) Workability and segregation.
   (*c*) Strength (and W/C relation) at different ages and under different curing conditions.
   (*d*) Permeability and absorption.
   (*e*) Shrinkage and volume changes, including plastic yield.
   (*f*) Fire resistance and fireproofing value.
   (*g*) Colour and texture and ease of finishing in various effects.
   (*h*) Modulus of elasticity and modulus of rupture.
   (*i*) Acoustical and insulating value.
   (*j*) Wear, dusting, abrasion.

7. Economy claimed by direct use of material.

8. Economy claimed as secondary result (or superior result claimed) :—
   (a) Due to saving in dead weight.
   (b) Due to saving of patching.
   (c) Due to omission of waterproofing.
   (d) Due to reduced size of members.
   (e) Due to omission of plastering or other finish.
   (f) Due to internal curing by water held in pores, etc.

9. Design aids in case new tables or diagrams are needed :—
   (a) For use of high-strength concrete, etc.
   (b) Different value of modulus of elasticity.
   (c) New column design diagram, etc.

10. Construction difficulties :—
   (a) Will it "gum up" the mixer ?
   (b) Practical "kinks" for field use.

Colouring Materials as Admixtures in Concrete.

At the present time there is an increasing demand for colour. This demand is making itself felt in every walk of life, and applies just as much to buildings as to furniture and pottery. Colour in concrete is receiving increased attention from all interested in the furthering of the use of the material, and this tendency is helping in no small measure to create a more or less well-defined "concrete style."

Since the bulk of the material in concrete consists of aggregates, it is the writer's opinion that these aggregates should be made to give the desired colours and textures, but a way of obtaining colour effects which is perhaps more obvious, but nevertheless probably not as satisfactory, is by the use of finely ground admixtures.

The two types of admixtures available are :—

1. Dyes.
2. Pigments.

Dyes.

In this class the only suitable type of dye is covered by patents.

The statement that dyes [66] can satisfactorily be used for colouring concrete has aroused keen interest throughout the building industry.

Those organic dyestuffs are used which have the greatest fastness to light, moisture, and other atmospheric effects, and which in the finished state are completely insoluble in water. The colour range of such dyestuffs available for use in the building trade is very extensive, and there seems no reason why concrete should not be tinted to produce any reasonable colour.

The process is simple, and is applicable equally to the colouring of concrete for use in mass or as blocks. The concrete is gauged with a solution of some simple derivative of the colouring matter. On exposure to the air, or by other simple treatment, the colouring matter is thrown down in a permanent insoluble form upon the cement particles.

By working with a solution of a colour derivative, or—in rather less exact language—a solution of the colour, one actually employs the colour in the most perfect state of sub-division possible. Although on precipitation there is doubtless a sort of coagulation, the precipitation occurs on the surface of the cement particles. The result is, that quite a satisfactory depth of shade can be produced by the use of no more than 0·1 per cent. to 0·6 per cent. of colouring matter, calculated on the dry weight of the concrete.

It is noteworthy that the depth of tint depends only on the ratio of dyestuff to cement, and, so long as this is constant, it is immaterial—as far as the colour is concerned—to what extent sand or other aggregate is added. Thus, a 7 : 1 mixture of sand and cement containing 0·06 per cent. of dye has practically the same depth of shade as pure cement containing 0·4 per cent. of dye. This brings out very clearly the dependence of methods of colouring concrete upon the surface area of the particles to be coloured, since the addition of, say, 86 parts of sand to 14 parts of cement increases the total surface area of the latter by only some 5 per cent.

In practice, the method would merely consist in gauging the cement or concrete with a solution instead of with water; and the dyes most suitable for this work would be those which can be brought into solution in the gauging water by simple treatment with a small quantity of alkali salts,

As the gauging is in progress and the concrete is being turned over, oxidation back to the original insoluble dyestuff takes place, and by the time the concrete is applied, the whole mass is coloured right through. In some cases the oxidation occurs with less rapidity, and the concrete may have to be applied before the original dyestuff is thrown down; but this presents no difficulty, as the oxidation will be complete before the material has finally set.

Pigments.

Requirements.—For success the pigments used should be able to withstand the action of both acids and alkalies. When the cement is setting, lime is liberated, giving an alkaline condition; later, the hardened surface will be attacked by acids in the atmosphere, thus giving acid conditions. The fact that the colour will be required to resist both of these actions rules out many organic colours which otherwise might be suitable. Further requirements are that the colour shall withstand successfully all weather conditions, including strong sunlight; that it shall be insoluble in water, and shall be of uniform quality.

Pigments may be :—

(1) Organic colours precipitated on a mineral base.
(2) Oxide colours.

Organic Colours.—In general these are unable to resist light and alkali, but if one is found which is successful under these conditions, it is almost certain that it will not be able to resist attack from any acids there may be in the atmosphere. We may assume, then, that this class is unsuitable for our purpose.

Oxide Colours.—These consist of the oxides of metals, such as iron, manganese, chromium, etc., and they may be natural or artificial. Ochre, which is a hydrated oxide, and umber, which is a mixed oxide, will come in this class.

As uniformity is of the utmost importance, it will be found that the artificial products are preferable to the natural colours. Further, the artificial colour is purer.

For important work it will probably be as well if the

buyer obtains a statement from the seller as to the composition of the colour.

Incorporating Colour.—The colour and the cement should be mixed together thoroughly in the dry state. The best way to do this is to grind the colour in by machinery. The builder may buy the colour and cement separately, in which case he will have to do his own mixing, or he may obtain a coloured cement.

The chief point in favour of coloured cement purchased from a reliable source is that a complete uniformity of colour is always assured. Against this is the fact that colours bought separately would generally show a saving on the total cost of the job.

If the cement and colour are mixed by the builder, the mixing may be carried out by machinery (which method is satisfactory, but generally would not be used on an average job), or mixing may be effected by hand. In either case definite weights, and not volumes, should be mixed together. For thorough hand mixing the cement and colour should be passed through a sieve two or three times. The mixture is then treated in the same manner as ordinary cement.

It is considered necessary to stress the point that the only certain way of getting an evenly covered finished surface is to employ machine mixing, and for important work this should always be done.

Good Quality Colour Necessary.—There are several reasons why a good quality pigment should be obtained. Pure colours are the cheapest in the long run and they give better shades in the finished work. The synthetically manufactured colours are purer, more finely ground and possess greater tinting strength.

The fineness of grinding is important, since the tinting power increases with the degree of fineness, and as fine grinding is expensive, this naturally will be reflected in the price of the colour.

Again, with few exceptions, the addition of pigments reduces the strength of the concrete, and though this reduction is not serious for small percentages, it is not considered good practice to use more than 10 per cent. of colour on the weight of cement.

Cost of Pigment.—This has been referred to already. It may be taken as an axiom that a good quality pigment, though expensive, will ultimately prove an economy. It is understood, of course, that each colour will have its own range of prices. A rough guide, decreasing in cost, is :—Green, black, red, purple, brown, red, yellow. The first red is a chemically prepared iron oxide of high purity, whereas the second is a cheaper pigment such as Spanish Oxide.

Strength of Concrete.—Tests were carried out recently by the *British Portland Cement Association, Ltd.*, to determine the effect of various pigments on the strength of concrete. First, plain check pieces were made, and then cubes and briquettes in which had been incorporated 5, 10 and 15 per cent. of the following pigments :—Red oxide, green chromium oxide, ultramarine blue, yellow ochre, black manganese dioxide, carbon black and marigold.

The results showed that both in compression and tension the concrete in which red oxide had been used gave as high results as the plain check test, but blue, green, yellow, manganese black and marigold gave slightly lower strengths. Carbon black definitely decreased the strength, and this decrease was more marked as the percentage of pigment increased. The average order of reduction in strength is :—Red, blue, green, yellow, black manganese dioxide, marigold and carbon black.

Various Pigments.—It is not possible to give a list of all the varying shades of colour which can be produced, and the pigments will be considered under the following heads :—white, black, green, blue, red, yellow, brown. Experiments with pigments of these colours and with white and grey cements will show that almost any desired shade can be produced.

White.—A clean white is not obtainable except by using a white cement. There are various methods of getting a near-white, but these are unsatisfactory.

Black.—The principal sources of black pigment are black oxide of iron, carbon black and manganese black. Manganese black, which is produced from manganese ore, consists chiefly of manganese dioxide, and this has given

good results. Carbon black consists of a form of soot such as lampblack. Common lampblack, in addition to having a tendency to float to the top during mixing, is apt to run and fade. Coal black, which is powdered coal, should not be used, except perhaps in the case of some of the anthracite coals. Ground coke is sometimes used.

In "*Concrete*," April, 1929, R. R. McCoy reports that tests indicate that black oxide of iron (analysing 98 to 99 per cent. Fe_3O_4), sufficient to produce a jet black, increases the tensile strength of cement. This is not the case with carbon or lampblack.

Green.—The best green pigment probably is chromic oxide green, as it is perhaps the most stable of all cement colour pigments. The pigment should be more than 99 per cent. pure chromic oxide (Cr_2O_3). Pure chromic oxide green is proof against heat, light, alkalies and all ordinary acids, and the use of small quantities probably will be found to increase the tensile strength of the cements.

A green which is not so good may be made by mixing ultramarine blue with yellow ochre. Lime green, which is sometimes used, is a magnesium aluminosilicate (augite), of very variable composition.

Blue.—Pure ultramarine blues should be used. The tensile strength of cement is increased by the use of reasonably small quantities of ultramarine blue. Prussian blue is also used. An entirely satisfactory blue has still to be found.

Red.—The most satisfactory results will be obtained by using pure red oxide of iron, *i.e.*, analysing more than 98 to 99 per cent. ferric oxide (Fe_2O_3). This pigment has strong colouring power and usually is entirely free from acid and does not carry more than 0·5 per cent. of moisture. The shades range from light orange undertoned red to dark blue undertoned red (Indian red).

Good results may be obtained if the ferric oxide is as low as 85 per cent., but it is risky to use colours containing lower percentages on account of the nature of the impurities present. These ferric oxide colours may have the content of ferric oxide varying from 40 to 100 per cent.

Venetian red should never be used because it is heavily

loaded with calcium sulphate, which often causes the cement to disintegrate. Crimson lake with alumina base is sometimes used.

Yellow.—The best colours are pure oxide of iron yellows. Yellow ochre and barium chromate are also used. Ochre and umber reduce the strength of the cement mortar; they are cheaper than the oxide of iron, but have comparatively little colouring strength. Zinc yellow (zinc chromate) is rarely used, as it is very expensive.

Brown.—Brown oxides of iron are best. High quality colours will contain 98 to 99 per cent. oxide of iron (Fe_2O_3). Burnt umber is safe, and gives a nice warm colour.

Tests for Pigments.—Pigments bought from a source of proved reliability will not usually require testing, but when investigating a new source of supply it is advisable to carry out a few simple tests.

Colours may be tested physically and chemically, and although some of the tests could not be carried out without special knowledge and apparatus, those mentioned below should suffice for the practical builder.

Organic Matter.—As mentioned previously, it is important that the colour should be of mineral and not organic origin. A simple test is to heat a sample of the pigment over a hot flame on a piece of porcelain or, preferably, platinum. Organic colours will be partially vaporised, whereas the mineral colours will only change colour or be unaffected; for instance, in the case of ultramarine green an entire change of colour takes place, but this is immaterial.

Another way of testing for organic matter is to heat a sample of the pigment in a solution of hydrochloric acid or in a strong solution of caustic soda. In this test oxide colours will not be affected to any appreciable extent.

Fineness.—The more finely the pigment is ground the better will it be for our particular purpose. High-class pigments, therefore, are generally ground so as to be much finer even than Portland cement, so that it is not possible to determine their quality in this respect completely by the use of sieves. Some indication of the fineness of the grinding would, of course, be given by passing a sample through the standard sieves used for cement testing.

A most satisfactory test from this point of view would be to test the colouring value of the material (see below).

Effect of Lime.—A simple test can be made by making two pats containing the pigment, one of them also containing hydrated lime. Allow these to stand for some time and then compare the colours.

Efflorescence.—The tendency of a colour to efflorescence can be tested by making a paste with a portion of the pigment and distilled water. Make the paste into a thin pat and place on a piece of clean glass to dry. If the colour is not good quality, efflorescence will appear at the edge of the pat after the water has evaporated.

Light.—A thorough test of the effect of light on a pigment is inconvenient on account of the time element, but an accelerated test may be made as follows:—Apply a layer of gelatine to a piece of paper and cover it with a layer of the pigment. Keep half of this in the dark and expose the other half to the sunlight (say in a photographic frame). A comparison made later will show if any bleaching has taken place. A good pigment should be able to withstand sunlight without changing colour.

Perhaps a more simple method would be to make an ordinary pat containing the pigment, which could be broken in two, one part being kept in the dark and the other in the light.

Colouring Ability.—The simplest method of testing the colouring ability of a pigment is to make up a pat in definite proportions, as, for instance, three of standard sand to one of Portland cement to 5 per cent. (on weight of cement) of pigment, and compare the colour with that of a standard pat prepared in a similar manner from materials of known quality.

The following is a more detailed test:—A pigment of known characteristics is mixed with zinc white in the proportions of 1 to 50, 1 to 10, 1 to 5, 1 to 2, 1 to 1 and 1 to 0, and these mixtures are spread with a little gum on white paper. The colour to be tested can be made up in the same way and the respective samples can be compared.

Weather.—Tests to determine the effect of the weather and the atmosphere of any particular locality can always

be made, but it is a long time before definite conclusions can be drawn.

Constant Volume.—A pigment containing foreign matter, such as plaster of Paris, may cause trouble owing to volume changes. For testing, mix five parts of cement to one of colour with water to form a pat and test for volume change in the ordinary way.

Aniline.—The presence of aniline [67] in cement colour is one of the principal causes of its not being light-proof. Aniline, however, can easily be detected by placing a little of the colour in each of three test-tubes (obtainable from any chemist for a few pence), one containing water, one turpentine, and the third alcohol. Each should be shaken thoroughly and then allowed to settle. If the colour settles at the bottom and leaves the clear fluid above in all three tubes, then the colour does not contain aniline. If, however, one of the fluids remains coloured, even if only slightly, the colour should not be used in conjunction with cement.

Conclusions from American Tests.[68]—The most important conclusions which may be drawn at present are :—

1. Most of the pigments used in these tests, and which probably are representative of those now on the market, are of a satisfactory degree of permanence, so far as may be judged by 6 months' exposure tests in 1-3 Portland cement mortars.

2. The following types of pigments were suitable from the standpoint of permanence after 6 months' exposure :—

Buff, yellow, red, .	Iron oxide pigments.
Green, . . .	Chromium oxide.
Blue, . . .	Ultramarine blue.
Brown, . .	Iron oxide, or iron and manganese oxide pigments.
Black, . . .	Iron oxide, manganese dioxide, carbon black, bone ash and the so-called "mineral blacks" (coal, coke, and certain unidentified carbonaceous materials high in mineral matter).

3. Cadmium lithopone, zinc chromate and organic colours are not suitable for general use in Portland cement mortar.

4. Among the pigments classed as of satisfactory permanence after 6 months' exposure, no difference in degree of colour permanence could be observed.

5. In cases where abrasion may result in exposure of the aggregate by removal of the coating of coloured cement paste, care should be taken to use aggregates of a neutral colour or of a colour which will harmonise with that of the pigment.

6. The ratio of pigment to cement is the most important factor affecting the colour of mortar produced by a given pigment.

7. The kind of cement and the mix and consistency of the mortar, are factors of secondary importance affecting the colour. Curing conditions and admixtures of hydrated lime make practically no difference in the colour, other conditions being the same.

8. Under some conditions quantities of certain mineral pigments in excess of the 10 per cent. generally recommended as a limit may be used without seriously impairing the strength. These tests are not broad enough in scope to serve as the basis of a general recommendation regarding the quantity of various pigments which may be safely added without serious reductions in strength.

9. In mortars containing the quantities of pigments usually used, the effects of water-cement ratio, mix, consistency and curing conditions on the compressive strength are about the same as on mortar without pigment.

10. Iron oxide black is preferable to carbon black, since equally dark-coloured mortar can be produced with the iron black with less reduction in the strength of the mortar. (Tests by the writer do not confirm this conclusion.)

Pozzolanas.

When Portland cement sets there is a certain amount of lime liberated. If there is something present in the concrete which can "absorb" this lime and render it ineffective, then the concrete will be better able to resist the action of many chemically destructive agencies. This is why a

" pozzolana " is sometimes used in the concrete mix, for, whilst not necessarily cementitious by itself, it possesses constituents which will combine with hydrated lime at ordinary temperatures in the presence of moisture to form stable, insoluble compounds of cementitious value (silicates and aluminates).

The pozzolanic action was known by the old Roman builders, and it has often been suggested that they possessed some secret for the mixing of lime mortar which has since been lost. The only secret, however, is that they used a suitable mixture of slaked lime and " pozzolana." The action of a " pozzolana " in a lime mortar is, of course, the same as in a Portland cement mortar, since it reacts with the " free lime."

Nature of Pozzolanic Action.—In *Bulletin No. 2* of the *Building Research Station*, A. D. Cowper and F. L. Brady point out that it is not quite clear to what particular ingredient or ingredients in the " pozzolana " the action of combining with the free lime is due. Certainly most active " pozzolanas " are rich in silica, and often show a considerable proportion of what is termed in analysis " soluble silica " ; but further investigations have shown that there is no distinct relationship between " soluble silica " and " pozzolanic " activity, at least in natural " pozzolanas." Alumina may be quite as active an ingredient ; thus aluminium fluoride, a pure chemical, when added to slaked lime, will immediately liberate an aluminium hydrate closely related to alumina, and actually impart rapid-setting qualities to the lime (Holmes and Fink, U.S. Patent No. 1,554,183, 1925). Many "pozzolanas" contain much alumina. A typical analysis of active natural " pozzolanas " will run :—

	Extremes of 31 Samples. Per cent.
Silica,	42-66
Alumina,	15-17
Iron oxide,	4-19
Lime,	3-7
Magnesia,	5-7
Water,	4-9

Since the degree of burning or particular thermal treatment has a very great influence on the activity of artificial "pozzolanas," it is possible that the activity may be due wholly or partially to certain chemically reactive complex compounds of silica, alumina and possibly alkalies; thus certain zeolites, which are hydrated silicates of alumina with alkaline earths, are markedly reactive with lime, and have been suggested for use as "pozzolanas."

Fire Resistance.—Another matter which must be mentioned is concerned with fire-resistance.[69] Portland cement concrete, although it is not combustible and tends to prevent the spread of conflagrations, is not in the true sense fire-resistant, for when exposed to high temperatures it loses strength rapidly. This is due partly to the conversion of the slaked lime in the cement to quicklime. The after-fire behaviour of the cement is also unsatisfactory for, when the previously heated cement is exposed to water or atmospheric moisture, the quicklime slakes, with expansion, bursting apart the concrete and completing the destruction which the fire has begun. The use of "pozzolanas," in conjunction with a suitable aggregate, has been shown to be a cure. By its means concrete has been prepared which, after heating to as high as 1,000° C., lost only a small proportion of its strength.

Recent Use.—Continental engineers have paid considerable attention to the use of trass in Portland cement concrete, probably owing to the fact that natural "pozzolanas" are available in numerous quarters. It is thought by many of them that up to a third of the Portland cement may be replaced by a suitable "pozzolana" without any serious loss in strength; and further, that if to the ordinary mixture suitable "pozzolana" is added up to one-third or one-half the volume of cement the various properties of the concrete will be greatly improved.

An important factor is the cost of the material, and for its employment on a large scale it seems certain that an abundant supply must be available near enough to any particular job to justify its use on economical grounds.

Types.—There are numerous " pozzolanas," and it would not be possible in a small space to refer to them all. The more important ones are mentioned below, and they have been divided into natural, artificial and dual type " pozzolanas."

Natural Pozzolanas.—Diatomaceous earth, which includes celite, infusorial earth, kieselguhr, moler, rottenstone and tripoli, is a finely divided sedimentary deposit composed chiefly of the siliceous skeletons of small aquatic plants. This material is found in Scotland, Ireland, Germany, Denmark, Bohemia, Tripoli, and California.

The Romans used a volcanic ash usually referred to as Italian " pozzolana " from the neighbourhood of Mount Vesuvius. Very old quarries are also to be found near Rome and Naples. Santorin earth is a sand obtained from the Greek island of Santorin.

" Trass " is perhaps the best-known " pozzolana " in this country. It is a volcanic rock (tufa) composed of pumice fragments and found in the Eifel district of Germany and Bavaria. It is recognised in official specifications on the Continent and has been used for extremely important work. Its use in this country has been limited, but the following instances may be quoted :—Aberdeen Harbour, Lancashire and Yorkshire Railway, Leeds Tramways, and Newcastle Waterworks.

It was pointed out in *Building Science Abstract No. 1,497*, August, 1928, that the difficulty of mixing " trass " with the other ingredients in concrete had led to a demand for ready-mixed " trass " cement. Tests carried out on such a cement indicate the increased resistance of the concrete to sea-water, etc. It is suggested, however, that the disintegration of surfaces above water level can be avoided only by the use of an impermeable coating which prevents evaporation.

The weight of a cubic yard of " trass " is about 14¼ cwt.

Artificial Pozzolanas.—Ground blast-furnace slag is our most important artificial " pozzolana," and it is used not only with lime, but also with Portland cement. If mixed with the Portland cement in certain proportions it comes within the definition of Portland blast-furnace cement, as

laid down by the *British Standards Institution*. There is a British Standard Specification for this cement, and apart from the chemical composition, the requirements are the same as those for the B.S. Specification for Portland cement (1931). The advantage claimed for this cement is that, owing to the pozzolanic action, there is much less free lime in the concrete than there would be with Portland cement.

Other artificial " pozzolanas " are crushed bricks and tiles, furnace clinker, spent oil shale, " link trass," " si-stoff," and burnt clays. Furnace clinkers vary considerably in their pozzolanic action, some of them not having any at all, so that they are quite unreliable. " Link trass," which is a mixture of finely ground blast-furnace slag and burnt clay, has been introduced into Germany as a substitute for natural " trass."

Ceramic Pozzolanas.—F. L. Brady [70] reports that of late years the attention of the *Building Research Station* has been directed to the problem of " pozzolanas," and, amongst other types, the " ceramic pozzolanas " have received a large share of attention. Methods have been evolved whereby the activities of " pozzolanas " can be measured with accuracy. From these experiments it has been found that by burning certain suitable clays at temperatures from 600° to 900° C. pozzolanic materials can be prepared of an activity exceeding that of Rhenish " trass." Since the latter material is so highly esteemed on the Continent, a home-produced " pozzolana," cheap and of a high activity, must surely be worth considerable attention. Fuller details of the methods of testing " pozzolanas " and the results obtained may be found in the *Report of the Building Research Board for 1926*, and in the *Building Research Paper* on " Pozzolanas."

Research on this question is by no means complete, but a number of data have been obtained. All clays so far tested seem, when burnt at suitable temperatures, to yield " pozzolanas," but the maximum activity obtainable and the temperature of burning which yields the maximum differ with different clays. The most active " ceramic pozzolana " so far prepared is a certain ball clay heated

to a temperature of 600° C., and this material appears to show an activity about 1½ times as great as that of Rhenish "trass."

Gaize.—Gaize, which is a "*dual type pozzolana*," is a natural siliceous material consisting of a clay cemented by gelatinous silica, found in the Ardennes. It has marked pozzolanic properties, particularly when burnt and ground. It is soft and porous, has a specific gravity of 1·5, and contains a large proportion of alkali-soluble silica. Tests carried out in France have shown that the resistance of Portland cement mortars to solutions of magnesium sulphate and calcium sulphate is considerably increased by the addition of burnt gaize.

Conclusions.—There seems little doubt that the use of "pozzolanas" will be extended for certain types of work. When Portland cement sets there is a partial splitting up of the lime-rich silicates, with a consequent liberation of slaked lime. We may assume that Portland cement, when set, contains about 7 per cent. of slaked lime in the free condition or, putting it more simply, 7 per cent. of "free lime." This free lime is a source of weakness in the concrete, and if it can be "absorbed" by some material present in the concrete so as to form an insoluble compound, it is reasonable to infer that the concrete will be improved. Tests on concretes in sea water would appear to leave little doubt on this matter.

Again, when subjected to a high temperature, the free lime is changed into quicklime. This change, resulting in shrinkage, lowers the strength of the concrete, and later, when moisture comes into contact with the quicklime, the latter slakes and expands, with consequent disruption of the concrete. Clearly, any method of rendering this free lime ineffective should be studied diligently.

As far as this country is concerned, the indications are that we shall depend mainly on ground blast-furnace slag and burnt clays for our "pozzolanas." The natural "trass" of the Continent is, in effect, a clay which has been heated by volcanic action, and the artificial production of this state is the obvious course to pursue here.

Miscellaneous Results.—As an indication of the results

obtained by the use of pozzolanic admixtures, the following conclusions are given for

1. Diatomaceous earth.
2. Gaize.
3. Moler.
4. "Si-stoff."
5. Trass.

Diatomaceous Earth.—Information has been sought [71] on the effect of additions claimed to increase the workability of concrete. Such additions frequently take the form of diatomaceous earth products. The subject is somewhat controversial, and contradictory results have been published. "Workability" is a difficult property to evaluate, and at present no unobjectionable method of measuring it is known. Experiments carried out at the *Building Research Station* have shown that the addition of a particular diatomaceous earth preparation to concrete makes a very radical change in the quantity of gauging water required for a uniform consistency, and, in fact, such an addition would have to be used with considerable caution. Data are not available regarding the mechanical properties of hardened concrete incorporating this addition.

A brief description has been given of a series [72] of compressive and tensile strength tests of various cement mortars and concretes in which diatomaceous earth was substituted for parts of the cement in proportions ranging from zero to 50 per cent. by weight of the cement, which was of two types, one containing a large percentage of free lime, the other a small percentage. It is thought that the results obtained tend to confirm the theory that, while admixtures of finely pulverised forms of silica result in many cases in increased cement strengths, admixtures of this type have but negligible strength effect when added to correctly proportioned cements, themselves containing sufficient silica to combine during burning with the whole of the lime present in the raw mix, but that, with incorrectly proportioned cements which, after burning, contain high percentages of free lime, such admixtures increase mortar strengths in proportion to the amount of free lime.

The following conclusions,[73] drawn from numerous tests, are of interest :—

1. With a constant water-cement ratio, the consistency of a mortar as expressed by flow decreases as the percentage of diatomaceous earth is increased.

2. The use of diatomaceous earth as an admixture in these mortars causes a puffing, or an increase in volume of mortar, which is slightly more than the absolute volume of admixture added.

3. The compressive strength of 1 : 3 and 1 : 4 (by weight) mortars containing small percentages of diatomaceous earth is approximately equal to or slightly greater than identical plain mortars of the same water-cement ratio.

4. No appreciable nor consistent difference in expansion when stored in water, or contraction when stored in air, was noted in these tests between plain mortar bars and mortar bars containing small amounts of diatomaceous earth as an admixture.

5. Shrinkage in air is generally larger than expansion in water for these mortars when subjected to alternate storage in water and air.

6. The shortening in time of set of these mortars increases with the amount of diatomaceous earth used.

It should be understood clearly that diatomaceous earth may be used purely for its pozzolanic properties, or merely as an admixture (in the restricted sense adopted by some American writers) for increasing the workability of concrete, etc.

To investigate the claims made for one of the proprietary articles, tests were carried out for the writer in the laboratories of *G. & T. Earle, Ltd., Hull*, to whom due acknowledgment is made for kind permission to use the results. The material was a very pure form of diatomaceous earth.

Experiments were carried out to see what effect the earth had when used as an admixture with concrete, on the following points in particular :—

1. Efflorescence.
2. Consistency.
3. Strength.
4. Segregation of aggregate,

1. It was found that 5 per cent. of the admixture (on the weight of cement) reduced the efflorescence of ordinary and coloured cement slabs, but did not entirely eliminate this trouble in all cases. It is certain, however, that a much improved surface is obtainable with the aid of such additions and, combined with good concrete practice, surface defects should be reduced to a minimum.

2. It was found that an addition of 5 per cent. of the admixture to a mix with the same water-cement ratio reduced the slump by 1½ inches to 2 inches, or, to obtain the same slump, about 10 per cent. more water was required. The slump test is, however, not necessarily a measure of consistency or workability, and it was observed that the addition tended to make the mix less harsh, even though the slump was also less. It is probable that a similar result could be obtained at lower cost by the use of more cement.

3. The general effect of the admixture was a reduction in concrete strength. It was found that at 1 inch to 1½ inches slump the strength was reduced by 20 per cent. at 7 days and 24 per cent. at 28 days, and at 5 inches slump the reduction was 33 per cent. at 7 days and 28 per cent. at 28 days. In the tests with the same water ratio, a 4 per cent. increase at 7 days was found in one case, but a 7½ per cent. decrease at 28 days was observed for the same series. In another case the reduction in strength was 17 per cent. and 18 per cent. at 7 and 28 days respectively. It is possible that, owing to chemical action between the soluble silica in the material and the lime liberated from the cement during hydration, and the consequent formation of calcium silicate, longer-date tests would show that the use of this material did not cause any loss in strength. This probable chemical action is the basis of the hope that efflorescence will be reduced, but the action is most likely of a slow nature, and thus the initial efflorescence, which occurs under favourable conditions in the first few days after mixing, is not entirely prevented.

4. It was noticed in the wetter mixes that there was less inclination towards segregation of the aggregates when the admixture was used. This may be a valuable property with ready-mixed concrete.

Gaize.—G. Baire describes [74] an extensive investigation undertaken by the *French Cement Association* to find a cement which should be as resistant as aluminous cement to the chemical action of sea-water, and be obtainable at approximately the same price as Portland cement. Tests are described illustrating the advantage gained by the addition of gaize to ordinary Portland cement. Analyses are given of three samples of gaize. The results of the tests indicate that the material is most effective when calcined at about 900° C. Comparative tests on gaize cement 1 : 3 mortars showed compressive strengths of 320, 253 and 206 kg./cm.^{2} (4,550, 3,600, 2,930 lbs. per square inch) after 10 years' exposure to fresh water, sea-water and air, respectively. The gaize cement consisted of equal parts of gaize and Portland cement. It is considered, however, that the best proportions are 2 parts by weight of Portland cement clinker to 1 of calcined gaize. The two materials are ground together so as to leave a residue of 8 to 10 per cent. on the 4,900-mesh/cm.^{2} sieve (31,650-mesh/sq. in.). A small proportion of gypsum is added to prevent too rapid setting. The results of tests at the Association's laboratories at Boulogne showed the average setting times to be 5 hours 35 mins. initial, and 8 hours 15 mins. final, and the average compressive strengths of 1 : 3 mortars to be 140, 256·3 and 325·5 kg./cm.^{2} (2,000, 3,640, 4,620 lbs. per square inch) at 7 days, 28 days and 3 months, respectively. The use of gaize cement, the chemical composition of which is given, is said to be increasing rapidly, and to require no special precautions, while the price is approximately the same as that of ordinary Portland cement.

Moler.—Moler is said to be preferable to "trass" for concrete exposed to sea-water. The alkali-soluble [75] content of the raw moler is over 50 per cent. and can be increased to more than 66 per cent. by sintering. The best results are obtained with mixtures of 75 parts Portland cement and 25 parts moler by weight. Admixtures of moler up to this amount increase the strength of the concrete, while any admixture of "trass" is said to result in a decrease. The concrete mixes used for the Yjmuiden locks contained

a mixture of $83\frac{1}{3}$ parts Portland cement and $16\frac{2}{3}$ parts "trass." The author is of the opinion that a small loss of strength will result, and that the amount of "trass" present is insufficient to produce the best results from the point of view of durability, but could not have been increased without a serious sacrifice of strength. The best mixture from the point of view of durability is said to be 58 parts Portland cement and 42 parts "trass" by weight.

"**Si-stoff.**"—It is suggested that, owing [76] to the difference in density, "si-stoff" is preferable to "trass" in lime or lime-cement mortars and concretes, but that "trass" is the better of the two for use with Portland cement. "Si-stoff" is said, however, to be especially suitable for use with high-magnesia Portland cements, in that it will counteract tendencies to unsoundness.

"**Trass.**"—An investigation [77] has been carried out at the *Research Institute* of the *Blastfurnace Cement Industry, Dusseldorf*, with a view to furnishing answers to the following questions:—

1. Can a portion of the cement be replaced by "trass," or should the "trass" be regarded as aggregate?
2. How much "trass" should be used to obtain the best results?
3. In which type of storage—air or water—does "trass" mortar harden best?
4. What are the effects on Portland and blast-furnace cements, respectively, of additions of "trass"?
5. Can "trass" be replaced by pulverised sand when the mortar is stored in air, water or magnesium sulphate solution?
6. Should the "trass" be added to the mortar on the building site, or is it better to grind the "trass" or sand together with the cement?

To this end, seven Portland and eight Portland blast-furnace cements were mixed with 0, 0·1, 0·25 and 0·4 part by weight of "trass" and pulverised sand respectively, and 1 : 4 mortars of these mixed cements and German standard sand were tested in compression after storage for periods up to 24 months in air, water and magnesium

sulphate solution. In order to ascertain the effect of the method of mixing, the same cements were ground with 0·1 and 0·25 part "trass" and sand respectively, and tested in the same manner. Series were also prepared in which 0·2 and 0·5 part of the cement were replaced by "trass" or pulverised sand. It is concluded from the results of these experiments—which are communicated in detail—that the foregoing questions may be answered as follows :—

1. The addition of "trass" increases strength; the replacement of cement by "trass" reduces it. As the addition of "trass" will also have a favourable effect on the porosity of the mortar, the addition is to be recommended. The replacement of a portion of the cement by "trass," which is but little better than the replacement of a like quantity of cement by pulverised sand, reduces both the strength and chemical resistance of the mortar, and must be avoided where such reductions are undesirable.

2. Additions of up to 40 per cent. "trass" increase strength and resistance to chemical attack, and the increases are proportional to the amount added. Pulverised sand produces similar effects in specimens stored in air or in water, but not in those stored in magnesium sulphate solution. The increases of strength caused by additions of "trass" are practically equal for Portland and Portland blast-furnace cements. The same amounts of "trass" may therefore be used, no matter which of these two cements is used. The amount of "trass" will vary with the requirements. Where chemical attack is to be feared, more "trass" will be necessary than when a decrease of permeability alone is required. In general, 25 per cent. on the weight of cement will suffice. The strength of both cements is reduced when a portion of the cement is replaced by "trass." The reduction is still greater if pulverised sand is used in place of "trass." The reduction of strength, due to replacement of cement by "trass," is smaller with Portland than with Portland blast-furnace cement. In general, it is not advisable to replace more than 0·2 of the weight of cement by "trass." If the mortar is to be exposed to magnesium sulphate, cement should never be replaced by "trass";

in this case the best results are obtained by adding " trass " to the mix. In this respect " trass " is preferable to pulverised sand. The sea-water resistance of Portland blast-furnace cement is increased by the addition of " trass." With Portland blast-furnace cement, smaller additions of " trass " are required to obtain the same increase of resistance to sea-water than are necessary with ordinary Portland cement. While 40 per cent. by weight is needed with ordinary Portland, 20 per cent. will suffice with Portland blast-furnace cement.

3. " Trass " mortars harden best in water. After a few months the " trass " participates in the hardening process and produces greater increases of strength than does pulverised sand.

4. In air storage the behaviour of the two cements is practically the same. In water storage the strengths of Portland cements with large additions of " trass " are a little higher than those of Portland blast-furnace cements with similar additions. The resistance of both cements to magnesium sulphate is increased by the addition of " trass." The resistance to sea-water is not favourably affected by the replacement of a portion of the cement by " trass."

5. The effect of " trass " as regards strength is but little more favourable than that of pulverised sand and is generally exaggerated. Its chief effect is that of a pore filler.

6. No advantage is obtained by grinding " trass " or sand with the cement ; the usual method of mixing the materials on the job is recommended. If ready-mixed " trass " cement is supplied, the quantity used for the mix must be increased by an amount equal to the " trass " content of the mixture.

Miscellaneous Admixtures.

Alum.—Alum, which is a double sulphate of aluminium and potassium, is a harmful ingredient of concrete and should not be used. When concrete is mixed at the end of

the day, with a proportion of alum, it can be left all night without attention and still be sufficiently plastic for use in the morning. The alum retards the set of the cement; but as it increases the sulphur content there is a possibility of subsequent disintegration. If a concrete having a delayed set be desired, the best thing is to get a slow-setting cement from a firm of repute.

Calcium Chloride and Frost.—The following summary appears in *Special Report No. 14* [78] of the *Building Research Station* :—

" Both calcium chloride and sodium chloride, when added in suitable proportions to the mixing water of a Portland cement mortar or concrete, afford protection against a limited degree of frost during the early setting and hardening periods.

" Sodium chloride is liable to cause efflorescences on the face of the concrete. Calcium chloride tends to produce discolorations.

" The commercial forms of both salts are hygroscopic, and unless the concrete is very dense, their presence in reinforced construction is liable to cause corrosion of the reinforcing metal, and particularly to intensify that due to stray electric currents. For reinforced concrete work it would appear inadvisable to use either salt.

" Concrete in which sodium chloride is incorporated generally appears to attain a considerably lower strength at long ages than similar concrete without this salt. Sometimes the reverse is the case with air-cured concrete; possibly, to a large extent, this is due to the falling-off in strength of the untreated concrete, on account of the occurrence of internal shrinkage stresses, rather than to increased strength of the treated concrete. Still, apart from the tendency of the hygroscopic properties of crude common salt to prevent excessive shrinkage, they may also cause some increased hardening to occur in specimens cured in air. The evidence of the tests which have been recorded by various investigators, however, shows that a serious diminution in strength often ensues, and on this ground alone, the use of sodium chloride is not to be recommended.

"Calcium chloride has numerous advocates, and many test results show an increase in strength due to its use, even after 1 to 3 years at normal temperatures. The best proportions appear to be 2 to 4 per cent. of the anhydrous salt per weight of cement. On the other hand, certain experiments have shown a decrease in strength, particularly of tensile strength.

"The employment of calcium chloride thus seems attended with some risk. The deterioration which is sometimes found may depend upon the presence of impurities, such as bleaching powder and, therefore, great care should be exercised if a crude commercial form of calcium chloride is employed.

"The action of the same product seems to vary with different brands of Portland cement, with the richness or otherwise of the mix, and with the consistency and probably also with the temperature and conditions of curing. It is difficult, therefore, to formulate exact rules, since not only has the significance of the undoubted variations not been determined, but the best results of different investigators are often contradictory."

Calcium chloride is no doubt a valuable admixture in some cases, but since exact fundamental knowledge of some of the reactions involved is lacking, it cannot be used without great care. To guard against failure, it would seem necessary that tests should be conducted upon materials identical with those to be used in practice, and under as similar conditions as possible; this refers particularly to the particular calcium chloride product and the brand of cement, also to the proportions of the mortar or concrete, including its water and calcium chloride content, and the curing conditions.

For aluminous cements no advantage results from the use of either calcium or sodium chloride, and the use of neither of these admixtures is recommended.

Calcium Chloride and Shrinkage.—Many experiments have been made to show the effect of calcium chloride on the strength and setting of concrete, but few have been made to discover what effect this admixture has on the shrinkage of concrete. Experiments [79] carried out in the

U.S.A. are therefore of particular interest. A summary of the results is given below.

Beams of 1 : 3 Mortar.—This series of tests showed that, at the end of 3 days, the shrinkage of the 2 per cent. beams was about 100 per cent. greater than that of the plain beams; at the end of 7 days, it was about 50 per cent. greater; and at the end of 14 days and thereafter it appeared to be constant, at about 85 per cent. greater than the plain beams. The test period was 18 days.

Beams of 1 : 2 : 4 Concrete.—Although the original water-cement ratio (0·936) was kept constant for all beams, the slump increased with an increase of calcium chloride. The results of these tests showed (1) that the addition of calcium chloride in amounts greater than 1 per cent. increased the shrinkage; and (2) that the greatest increase resulted from using 4 per cent. calcium chloride, which, at the end of 3 days, increased the shrinkage over plain concrete by about 155 per cent., at the end of 7 days by about 300 per cent., and at the end of 21 days by about 150 per cent.

Test Cylinders of 1 : 2 : 4 Concrete.—At the end of 3 days, the shrinkage of 2 per cent. cylinders was about 100 per cent. greater than that of the plain cylinders, at 7 days about 35 per cent. greater, at 14 days about 60 per cent. greater, and at 20 days about 45 per cent. greater.

Conclusions.—1. The shrinkage of concrete is greatly increased when calcium chloride is used in the mix.

2. Considerable increases in shrinkage are apparent when the optimum percentage of calcium chloride is used.

3. While the use of small quantities of calcium chloride in concrete mixes which are made for pavements may not be objectionable, in cases where shrinkage is an important factor the use of the chemical is not advisable.

Casein.—In an article entitled "Tests on Casein as an Admixture," in "*Concrete,*" June, 1926, W. E. Haskell reports that tests indicate that limited quantities of casein are found to increase workability, hasten setting and decrease the tensile strength of the concrete. The following mixtures were used :—

Mixture No.	Per cent. Cement.	Per cent. Casein.
1	100	...
2	97½	2½
3	95	5
4	92½	7½
5	90	10
6	85	15
7	80	20
8	65	35
9	50	50

The following tabulation illustrates in condensed form the results of the experiments. Mixtures 5 to 9 were found to be unsound.

	Mixture.			
	No. 1.	No. 2.	No. 3.	No. 4.
Normal consistency, per cent. .	23	21	20	21
Initial set, hours and minutes, .	4.0	2.5	1.45	2.0
Final set, ,, ,, ,, .	7.0	6.0	5.15	12.30
Constancy of volume, . . .	O.K.	O.K.	O.K.	O.K.
Tensile strength, 24 hours, lbs./sq. in.	395	310	150	...

Common Salt.—See "Calcium Chloride and Frost."

Iron.—Iron used for waterproofing concrete is in a highly pulverised state [80] and is simply mixed with water and applied with a brush. The principle involved in this method of waterproofing can readily be understood. The water in this mixture, when it soaks into the walls, carries these fine iron particles along with it, and when they rust they swell up to several times their previous size and seal the pores completely. This rusting process is hastened by the addition of chemicals, as otherwise it would be too slow for practical purposes. As iron oxide or rust has little or no tendency to change under normal conditions, the waterproofing does not deteriorate with age. Consequently, it is claimed that a wall or floor waterproofed with this material

will remain waterproof permanently. The coating of rust may be covered by a plaster coat.

Another use for this pulverised iron is in repairing broken walls and floors and filling cracks. In this case it is not used of course for its waterproofing qualities, but for its ability to create a perfect bond between the old material and the new material in the patch. For the patch itself some iron is mixed in with the usual concrete ingredients.

Still another use for pulverised iron is as a floor hardener. For this purpose slightly larger particles are used. The iron is scattered over the top coat before it sets and is then trowelled in. This simple and inexpensive treatment not only gives the floor a wearing surface which will stand hard usage, but makes it practically oil-proof, waterproof, and dust-proof.

Lime.—The efficacy of hydrated lime [81] as a waterproofing agent in concrete is claimed to be due to two distinct properties inherent in the lime itself. These properties are :

1. The extremely minute size of the individual particles, and the colloidal or gelatinous (glue-like) nature of the most infinitesimal of these particles when thoroughly saturated with water.

2. The natural viscosity or stickiness of the lime putty produced when lime is mixed with water.

It is a simple matter to demonstrate the fact that a No. 200 sieve will hold water, this seeming paradoxical performance being possible because of the small size of the openings in the sieve. Again, a No. 325 sieve will hold more water (*i.e.*, a pressure head of water) than a No. 200 sieve, the increased impermeability being due to the fact that the No. 325 sieve has even smaller openings than the No. 200. Hence, it becomes obvious that the more minute the openings (*i.e.*, the pores or air spaces) in a material, the more resistant it is to the passage of water through it.

In this discussion, concrete is the material to be rendered impermeable, and, for maximum efficiency, the constituent materials will be so proportioned and graded that the air spaces between the stone particles will be just filled with sand, and the air spaces between the sand grains will be

just filled with cement, leaving only the air spaces between the very small cement particles for the passage of water. This optimum condition is realised only in relatively dry concrete mixes, rich in cement and thoroughly mixed to give a homogeneous material throughout. Even then the addition of a small amount of hydrated lime improves the impermeability quite measurably; for the lime particles are far more minute in size than the cement particles, and therefore act to fill the air spaces between the cement particles, leaving only the most infinitesimal air spaces between the lime particles for the possible passage of water. In addition, the increased colloidal (glue-like) content supplied by the lime not only acts to seal these infinitesimal air spaces, but also makes the concrete more viscous and sticky, and hence prevents the separation (unmixing) and segregation of the component materials, and the consequent laitance layers, "honeycombing" and porosity so often found in plain concrete.

There is no exact rule for the proper amount of hydrated lime to add in any specific case, as an accurate sieve analysis not only of the stone and sand but also of the cement and lime would be required to determine precisely such quantity, and no method for the complete analysis of the fineness of cement or lime has as yet been devised. It has been found in practice that the most satisfactory results are usually obtained by the use of the formula $L = 6\,(S - \frac{1}{2})$, where L is the weight in pounds of hydrated lime per sack (94 pounds) of Portland cement, and S is the proportion of fine aggregate in the concrete mix. Thus, for a $1 : 2\frac{1}{2} : 5$ mix, $L = 6\,(2\frac{1}{2} - \frac{1}{2}) = 12$ pounds hydrated lime per sack of cement. This formula holds good for the water-ratio and fineness modulus methods of proportioning, as well as the older method of arbitrary proportions.

Silicate of Soda.—Silicate of soda, used as a surface hardener and applied to the finished concrete, is of real value, but when used as an admixture with the various ingredients for concrete it is a disadvantage.

Tests carried out at the Laboratory of the *Association of German Portland Cement Manufacturers* in this connection gave results as follows [82] :—

An ordinary Portland cement was used and water-glass was added to the mixing water in quantities of $\frac{1}{4}$, $\frac{1}{2}$ and 2 per cent. The following conclusions were drawn :

1. The time of setting is not affected appreciably by $\frac{1}{4}$ to $\frac{1}{2}$ per cent. water-glass ; it is accelerated by higher percentages (2 per cent.).

2. The compressive strength is considerably reduced in all cases. A 2 per cent. admixture reduced the strength at 2 days to 80 per cent., at 7 days to 76 per cent., and at 28 days to 66 per cent.

3. The tensile strength is not appreciably affected by the admixture of water-glass. (Tests made by *G. & T. Earle, Ltd.*, show that the tensile strength is reduced.—Author.)

4. Contrary to the information commonly encountered in laboratory hand-books, water-glass used as an admixture in the mixing water is detrimental to the strength of concrete.

5. This does not apply to water-glass when used as a surface coating to increase the hardness of concrete, a process which appears to have given good results on concrete roads in England. The alkali liberated during the application of the surface coating is made harmless by the carbon dioxide of the air, while in the concrete it forms compounds which impair the strength.

Washing Soda.—Washing soda has often been used to hasten the setting of Portland cement concrete, but there is little to recommend its use, since a cement having any required setting time (within reasonable limits) may be obtained from the makers. An amount of soda required to make one cement quick-setting often causes another cement to have a flash set ; hence a series of experiments is necessary. Further, ultimate disintegration of the concrete is probable.

Waterproofing Admixtures.—The question of waterproofing concrete is quite a large one and cannot be referred to in detail here. One method is to use a special type of admixture, and some of these materials are mentioned below :—

1. *Aluminium Stearate.*[83]—This material fills the pores of the concrete with water-repellent substance without hindering the set of the cement.

2. *Special Paste.*—A watery paste consisting of 40 per cent. barium carbonate, 15 per cent. oleic acid, 10 per cent. sodium silicate (thinned with half its volume of water) and 35 per cent. water.

3. *Special Mixture.*—A mixture of fine sand, common laundry soap and alum. The soap should be composed of 50 per cent. soap, 40 per cent. water and 10 per cent. sodium silicate. One part of soap dissolved in boiling water is added to 3 parts of fine sand by weight. The mixture is allowed to cool and become hard, and is then ground to a fine powder; to two parts of this powder one part of powdered alum is added. The resultant powder is used in the proportion of $2\frac{1}{2}$ kilograms to 1 cubic metre of concrete, filling the pores with water-repellent aluminium oleate.

4. *Special Mixture.*—A mixture of sodium carbonate and aluminium sulphate, proportioned $1 : 1\frac{1}{2}$. This is added to 100 parts of cement. The treated cement is used in the ordinary way.

There are numerous waterproofing admixtures on the market, some of which are valuable and others not. One that is well established and widely known can be used without fear, but for a "new-comer" an investigation is desirable.

U.S.B. Standard Circular, 1928, No. 360 was referred to recently in *Building Science Abstracts.* This specification, numbered *444a*, supersedes *No. 444* of the *Federal Specifications Board* and requires that integral waterproofers for use with concrete mixes shall be stable compounds, which mix readily with either water or dry Portland cement, become an insoluble integral part of the mortar or concrete, and shall not impair the durability or reduce the compressive strength more than 10 per cent. Specimens treated with the waterproofer shall show an absorption of not more than 3 per cent., and the permeability shall be reduced at least 95 per cent. of that of test pieces made without admixture of the waterproofer but otherwise identical. Rules are given for selecting samples for carrying out tests for absorption, permeability and compression, and for packing and marking consignments.

CHAPTER VIII.

WATER AND IMPURITIES.

General.

Quality and Quantity of Water.—This chapter deals with the quality of the water used for making mortar and concrete. In almost all instances a slight impurity is of little consequence, and the quantity of water used in the mix is of far greater importance than the quality. There are a few cases, however, where impurities must be considered, and a few of these will be mentioned. The list could be extended almost indefinitely, but as most of the special " waters " are not likely to be found in use on the average job, the following examples must suffice.

Specification.—Little need be said regarding the specification clause for mixing water, the two following suggestions covering almost all cases :

1. Water used [84] in the concrete shall be taken from a source which has proved satisfactory on similar work. Surface water shall not be used, nor water subject to pollution by industrial waste, except after tests satisfactory to the Engineer. Where town water is used it shall be paid for by the Contractor.

2. Water [85] for concrete shall be clean and free from injurious amounts of oil, acid, alkali, organic matter or other deleterious substances.

Examples of Waters.

Distilled Water.—Long-period tests which were reported in " *Le Genie Civil* " [86] a short time ago showed that distilled water had a decidedly disintegrating effect on cement mortar briquettes, whereas ordinary river water with a

calcareous content had no effect. The cements used included natural, slag, limestone, quick-setting and aluminous, and the tests extended over a period of approximately two years. At the end of this time it was found that, with one exception, all the briquettes made with distilled water had become badly pitted, the exception being those made with "*Ciment Fondu.*"

The following explanation is given to account for the varying state of the briquettes. Pure waters, containing only insignificant proportions of carbonic acid, act as solvents on the lime in the mortar, whereas reasonably calcareous waters in contact with this lime precipitate insoluble calcium carbonate, which closes the pores of the mortar and thus protects it instead of altering it. Owing to its special constitution there is no lime liberated during the setting and hardening of aluminous cement, and therefore it is not attacked by pure water.

Tests, the results of which do not agree with the foregoing, have been reported by A. J. Blank, in "*Rock Products.*" [87] Four groups of specimens prepared as follows were used, namely :—

1. Mixed with and stored in distilled water.
2. Mixed with distilled water and stored in river water.
3. Mixed with and stored in river water.
4. Mixed with river water and stored in distilled water.

The results of the tests showed that, whichever the mixing water used, for the specimens stored in distilled water there was no loss of strength in the 28-day and 3-month tests.

In view of these apparently conflicting results it is clear that much further experimental work requires to be done on this matter.

An investigation [88] has been carried out in which the tensile and compressive strengths of mortars gauged with Karlsruhe tap water and with distilled water have been determined by the methods laid down in the German standard specification for Portland cement. The results show that, when tap water was used, higher compressive strengths but lower tensile strengths were obtained.

It is further evident that the effect of tap water varies with different cements. As tap water differs considerably in different towns, it would appear that a standard water should be specified for cement testing, and it is proposed that distilled water should be prescribed for this purpose. Tests have shown that the nature of the water in which tensile test specimens are stored has practically no effect upon the strength.

Humic Acid.—The presence [89] of quantities of humic acid as small as 0·078 per cent. seriously affects the strength of the cement mortar produced. Chemical action due to the acid retards setting and reduces the ultimate strength. Sand which has been in contact with peat or arable soil is, as a rule, unsuitable for cement mortar, since this acid, which is present, is only slightly soluble in water, and consequently is not removable by ordinary washing. It has been shown that sand containing 0·1 per cent. (by weight) of humic acid is quite useless for cement mortar, even small quantities of humic acid affecting detrimentally the setting of the cement. Other impurities in samples of natural sand did not produce any noticeable difference in the strength of the mortar, provided the humic acid was removed by washing the sand with milk of lime.

Moorland Water.—Organic acids, although their effect is not so rapid as mineral acids, have, nevertheless, a harmful action, and in this category must be placed the humic acids present in peaty water. The action of any disintegrating agent upon concrete is always rendered less virulent if penetration into the body of the concrete is prevented, and concrete which is perfectly impervious has a very long life, even in contact with very harmful solutions. In the problem of dealing with moorland water, therefore, the concrete should be made as dense as possible by a judicious choice of aggregate, and the proportion of cement should be increased above what would normally be required to give the requisite strength. Thus a mixture of 4 parts of coarse aggregate, 2 parts of sand and 1 part of cement is quite satisfactory under ordinary conditions, but in this particular circumstance a $3 : 1\frac{1}{2} : 1$ mixture will be very much better. The same general problem is met with in

connection with concrete in contact with sea-water, and material which is dense and rich in cement has been found to resist the arduous conditions exceedingly well. The treatment of the finished surface of the concrete can be improved to resist the action of acid by the application of a solution of silicate of soda (see p. 155), since this combines with some of the liberated lime and makes the concrete considerably denser, but it will not make porous concrete and lean concrete resistant to acid solutions.

Nitrogen Pentoxide.—The failure [90] of a particular batch of concrete to harden satisfactorily was traced to the use of the purified effluent of an artificial fertilizer factory as mixing water. The water was found to contain nitrogen pentoxide which varied considerably in amount from day to day. It was found on investigation that contamination with nitrogen pentoxide up to about 0·75 per cent. produced no harmful results, but that larger quantities seriously retarded setting. Setting test pats gauged with the contaminated water developed crusts of crystalline calcium carbonate, and concrete mixed with this water lost abnormally large quantities of lime by leaching out during water storage. Further investigation of these phenomena is in progress.

Salts.—Compression tests [91] have been carried out on water-cured 1 : 3 Portland cement-sand mortars gauged with distilled water containing in solution 0, 0·5, 1, 2 and 4 per cent. respectively of the negative ion of each of the following salts: sodium chloride, sulphate and carbonate, magnesium chloride and sulphate, ferrous sulphate. All the sodium salts used were found to be injurious to Portland cement mortars, equivalent (ion) quantities of the chloride, sulphate and carbonate causing progressively greater reductions in strength. The two magnesium salts exercised but little effect, whilst calcium chloride and ferrous sulphate were found to be beneficial. Attention is drawn to the fact that all brands of cement may not be affected in the same way. It is further concluded that the strength ratios tend to increase with age, *i.e.*, for a salt that reduces strength the effect is less for greater ages, and for salts which improve strength the increase at 3 years is usually

greater than at 28 days. Sulphates, *per se*, are not necessarily injurious to mortar strength ; 2 per cent. of the sulphate ion in the form of ferrous sulphate, *i.e.*, about 6 per cent. of the salt, increases the strength by 20 per cent.

Sea-Water.—Although specifications usually forbid the use of sea-water for gauging concrete, it has not been definitely established that there is a particularly harmful effect resulting from this practice. In the *Proceedings of The American Concrete Institute, 1924*, D. A. Abrams reported a series of tests on impure waters for mixing concrete, and gave the following conclusions for sea-water :—

"Concrete mixed with sea water (about 3·5 per cent. salts, mostly sodium chloride) and cured in the moist room, gave higher strengths than fresh-water concrete at ages of three and seven days ; at 28 days and over, the strength ratios for sea water ranged from 80 to 88 per cent. Air-cured concrete mixed with sea water was lower in strength than similar fresh-water concrete at 3 months, but showed a recovery in strength at later ages and gave strengths equal to that obtained with fresh water. (In spite of the satisfactory strength results, it seems unwise to use sea water in reinforced concrete construction, particularly in the tropics, on account of danger of corrosion of reinforcement.)"

Sugar.—There is no doubt that sugar has a most deleterious effect on concrete, as is shown in the following examples :—

Case 1.—Repair [92] shops of Cuba Northern Railroad at Moron in the Province of Camaguay. Some of the foundations developed deficiencies ; the concrete would not harden, and finally complete disintegration of that part of the concrete followed. By a careful inspection of the different materials separately, it was found that the sand contained foreign matter, which proved to be sugar. As a matter of fact, one of the freight cars used in the transporting of the sand had previously hauled sugar, leaving a coating of sugar on the floor. The wet sand, by capillary action, absorbed a certain amount of the sugar, sufficient to destroy totally the chemical action of the cement. The sugar content was about 2 per cent. of the sand.

Case 2.—A case [92] which occurred in 1913 is reported by

Charles A. Newhall. An important piece of construction failed by disintegration of the concrete. The aggregates were all of excellent quality and subjected to a rigid inspection. It transpired, however, that the cement had been transported in a steamer which previously had carried a heavy cargo of sugar. Some of the cement bags had burst and were afterwards refilled with cement containing sweepings from the floor, and it is unnecessary to state that this was the cause of the disaster.

Case 3.[93]—Another case in an important work in Cuba is interesting, because the engineer in charge had heard of the case at Moron, and was taking every possible precaution to avoid any possible contact between sugar and the concrete. The lumber which was used for forms had been stored in a sugar warehouse, but had been washed before being used in the work, However, six days after pouring the concrete, the engineer noticed that he could easily remove a layer $\frac{1}{2}$ inch to $\frac{3}{4}$ inch thick from the concrete surface, showing that the material had not set. After removing the forms, the concrete under the soft layer proved to be as hard as rock, showing that the minute quantity of sugar that might adhere to the boards had been sufficient to destroy the action of the cement for a thickness of more than $\frac{1}{2}$ inch.

Tannic Acid.—It has long been recognised[94] that impurities of an organic nature have the effect of reducing the strength of concrete or entirely destroying the hydraulic properties of the cement. The following are the principal conclusions from an American investigation :—

1. It is believed that the results of the tests are typical of the effect produced by organic impurities on concrete.

2. The strength of the concrete was reduced for all percentages of tannic acid, and for all mixes and ages covered by the tests. Less than 0·1 per cent. of tannic acid in terms of the weight of the aggregate may reduce the strength of the concrete to one-half its normal value.

3. Lean mixtures are more affected by tannic acid than the rich ones.

4. The mixtures from the finer aggregates are less affected by tannic acid than those from the coarser aggregates.

5. All of the effects just mentioned may be summed up by saying that the reduction in strength of the concrete is a function of the concentration of tannic acid in the mixing water. An equation is given which represents this relation for the 28-day tests.

6. The results of the tests indicated that the wetter consistencies would be less affected by the presence of organic impurities than the drier ones.

7. The strength falls off rapidly for small percentages of tannic acid and less rapidly as higher percentages are reached.

8. The 7- and 28-day strengths are reduced to a greater extent by tannic acid than at ages of 1 and 2 years.

9. Some of the 1 : 5 mixes in which the higher percentages of tannic acid and the finer sands were used (2 to 3 per cent. solution) disintegrated before the time of test. The 1 : 7 mixes (3 to 5 per cent. solution) were destroyed in removing the moulds.

CHAPTER IX.

DESIGNING CONCRETE.

General.

A CONCRETE may be designed for any particular purpose, but it does not follow that a concrete designed and made for compressive strength, for instance, is going to be suitable for water-resisting work. The relations which may exist between the various concrete properties are but imperfectly understood, and attempts have frequently been made to find laws connecting these properties when the data available have been far too meagre. Numerous variables have to be considered, even when carrying out the simplest experiments, and unless these are eliminated one by one the resulting conclusions are likely to prove misleading in that they will be based on false premises.

The water-cement ratio theory, or, more simply, the water-ratio theory, discussed later, deals fundamentally with compressive strength. This should be remembered, as future research will probably disclose apparent discrepancies, which will no longer exist when the problems are fully understood. Great economies may often be secured by considering the type of structure when designing the concrete mix.

Importance of Water Content.

Figure 3 illustrates the effect of the amount of mixing water on strength. The water-ratio theory applies *only* over the portion XY. The curve illustrates quite clearly that there is a maximum strength obtainable, and that as the water content is reduced below, or increased above,

the amount necessary for this maximum strength, the resulting strength is lowered.

The portion of the curve to the left of the maximum point applies to concrete blocks, etc., made by the dry process, so that the addition of more water to such concrete will result in increase in strength. Hence it is generally

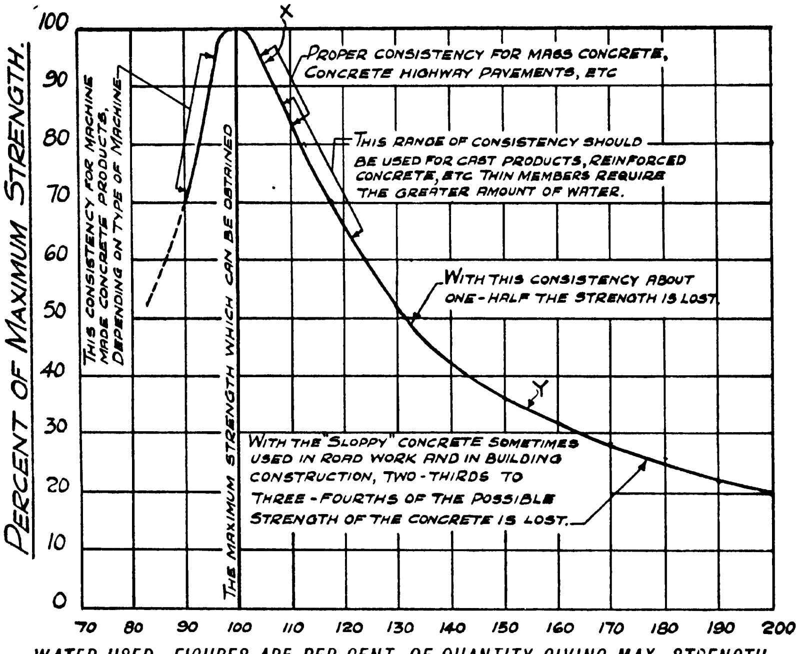

Fig. 3.—Water and Strength.

advisable to make this type of concrete as wet as manufacturing conditions will allow. The use of too little water results in the particles of aggregate not being sufficiently well lubricated to consolidate themselves in such a manner as to get maximum density in the concrete. There will be a high percentage of air voids, and the concrete produced will be relatively porous. If the amount of water is reduced too far, there is the possibility that there will not be enough

present to enable the complete chemical action of setting and hardening to take place.

On the other hand, blocks made by the wet process will lie on the portion of the curve to the right of the maximum, so that for this process a reduction of water content is advisable. The use of excess water means that a volume of concrete of maximum strength which would occupy one cubic foot might increase in volume to 1·1 cubic feet. On drying out, the excess water evaporates, leaving extra air voids to the extent of 0·1 cubic foot in the total volume of 1·1 cubic feet. The result is that here again we have a porous concrete. Excess water also reduces the strength and increases shrinkage troubles.

We thus see that from the point of view of compressive strength, and also of density, a block made by the dry process should be as wet as possible, and one made by the wet process should be as dry as possible. The loss in strength is appreciable, since with very wet mixes a value equal to about one-third of the maximum may be obtained.

The following is a practical discussion of the "Water Ratio," suitable alike for the Student, the Engineer and the Foreman. For further details reference should be made to the writer's book "*Reinforced Concrete Roads*," published by *The Contractors' Record, Ltd.*, 329 High Holborn, London, W.C. 1.

Water Ratio.

Abrams' Water-Cement Ratio Theory states that the strength of a concrete mixture depends on the quantity of mixing water in the batch, expressed as a ratio to the volume of cement, so long as the concrete is workable and the aggregates are clean and structurally sound. The strength of the concrete decreases as the water ratio increases.

Mixes too harsh or too stiff [95] for proper moulding, and those so wet that segregation occurs during or after placing, do not give strengths in line with the law. The importance of plastic mixes cannot be over-emphasised. Within similar

limits of workability, the water-cement strength ratio law applies equally to mortar and to concrete mixes. The tendency of wetter mixtures to segregate is specially noticeable in mortar mixes.

Aggregate grading affects the water-cement ratio strength curve. Mortar mixes of particles of one size only, and concrete mixes with wide gaps in aggregate sizes, give curves lower than those for mixes with a degree of continuity in particle size distribution. Differences in the curves encountered with different materials and under different test methods emphasise the desirability of using as a basis for design a curve providing some margin for contingencies.

Representation of the Water Ratio.—The water-cement ratio is merely the ratio of water to cement in a concrete mix. Much needless confusion has been caused because the original American values have been reproduced in this country without suitable modification. Abrams determined his water ratio by measuring the *volume* of water used per cubic foot of cement. To many an English reader this introduces two minor difficulties, the first being that he is not accustomed to thinking of volumes of water, and the second that a cubic foot of cement is a variable quantity as far as weight is concerned. The latter trouble is avoided by taking the weight of a cubic foot of cement as some recognised figure. In America this figure is 94 lbs., in England it is 90 lbs. for normal Portland cement, and 80 lbs. for rapid-hardening Portland cement. To prevent confusion the value of 90 lbs. will be used here. A further point to note is that American gallons are not the same as Imperial gallons (6 American gallons = 5 Imperial gallons).

There is no reason why the water ratio should be expressed as a volume relation, apart from custom. A weight relation is more easily understood, and is just as satisfactory. A practical man can visualise and appreciate " 7½ gallons of water to 1 cwt. of cement," where he will be lost if the same relation is expressed " 1 cubic foot of water to 1 cubic foot of cement." In the laboratory, the weight relation is still suitable, and instead of " 1 cubic foot of water to 1 cubic foot of cement," we can say " ⅔ lb. of water to 1 lb.

of cement." An effort should be made to remember this basic relation, as all other water ratios in any unit may easily be obtained from it. A water ratio of *one by volume* is the same as a water ratio of *two-thirds by weight*, and this equals $7\frac{1}{2}$ *gallons of water per cwt. of cement.*

Mathematical Equation.—Abrams considered, as a result of thousands of tests, that the relation between the water ratio and the strength of concrete could be expressed by

$$S = \frac{A}{B^x}$$

where S = Compressive strength of concrete at 28 days in lbs. per square inch for standard curing conditions.

A = Constant.

B = Constant.

x = Water ratio by volume (an exponential).

For average conditions for tests made in the laboratory this equation becomes

$$S = \frac{14,000}{7^x}.$$

It must be borne in mind that these constants refer to one set of conditions. Experimenters in this country would find different values for A and B. It is clear that the strength of the concrete will be raised by

1. Increasing the quantity of cement.
2. Decreasing the quantity of water.

When this point is fully appreciated the reader will have gone a long way towards understanding the water-ratio theory.

Effective Water Ratio.—The strength of the concrete will be determined by the water ratio when the concrete is in place and thoroughly consolidated. Water which is

extracted from the mix during transport from the mixer to the forms, or after the concrete is in place and whilst it is still plastic, in a manner which allows consolidation, should be deducted in determining the effective water ratio. For wet mixes this extraction of water will prove beneficial so long as consolidation is possible without loss of plasticity. The extraction may account in many cases for the strength of concrete on the job being higher than would be indicated by the state of the concrete as it leaves the mixer, since ordinary wood shuttering allows excess water to escape to an appreciable extent. Extraction of water beyond the point where consolidation can continue is to be avoided, as it will leave voids in the concrete.

Fineness Modulus.—The method of designing concrete mixes by the water-ratio theory has frequently been called the "Fineness Modulus Method" of design. This is entirely misleading, since there is no necessary connection between fineness modulus and water ratio, in that either procedure may be followed without reference to the other. The fact that the two can be used together advantageously, and the fact that Abrams refers to them both in the same publication, has led to needless complications and misunderstandings. As already mentioned, the fineness modulus of an aggregate is merely a number indicating the sieve analysis in a convenient form. It should be clearly appreciated that a concrete mix can be designed by the water-ratio theory without any reference at all to fineness modulus.

Designing a Concrete Mix.—The design of a concrete mix can be treated in two distinct portions, as under :—

1. Determine the water ratio so as to get a specified strength. This can be obtained either from the results of previous tests, from a mathematical equation, or from some preliminary tests made specially for the purpose. This deals essentially with the strength.

2. Having fixed the strength, the proportions of coarse aggregate, fine aggregate and cement should be determined in some suitable manner, *i.e.*, by trial or by use of the "fineness modulus." This deals with the economy of the mix, and is quite apart from the first step, which is concerned only with strength.

On the job workability is of prime importance, and must be considered when fixing the proportions of aggregates and cement. It has been suggested that workability is not considered in the water-ratio theory, but this is untrue. The water ratio applies only on the portion of the curve marked XY in Fig. 3, and on this portion workability can be controlled by the amount of water used per hundredweight of cement.

Aggregates and Water Ratio.—Although the basic idea of the water-ratio theory is easy to understand, the various implications are perhaps difficult to follow on account of the new viewpoint which has to be acquired.

The capacity of an aggregate for absorbing water is of importance. Water which is absorbed is extracted from the mix, and, since this is equivalent to reducing the amount of mixing water, the water ratio will be reduced.

The surface characteristics and the amount of dust present affect the adhesion of the cement to the particles of aggregate. The size and shape affect the area of aggregate in contact with the cement, and this affects the bond and the amount of cement required. Large, unbroken areas of aggregate surface tend to cause planes of weakness.

For a definite water ratio and a plastic mix, the grading of the aggregate can vary within wide limits and yet not affect the strength of the concrete to a large degree. The time when grading becomes important is when it is changed enough to cause an alteration in the quantity of paste required to make a plastic mixture.

From the point of view of the compressive strength of concrete, the strength of the aggregate particles has little effect except with very weak aggregates. If allowance be made for any alteration of water ratio caused by absorption, it can be assumed that ordinary sizes of the usual aggregates will give *approximately* the same compressive strengths in concretes made under the same conditions (variations are discussed later).

Specification.—The practicability [96] of this method has been shown by its use as the basis of a specification in the construction of the reinforced concrete building for the

Portland Cement Association, Chicago. The quality of the concrete was fixed by three simple requirements :—

1. Mixing water limited to 6 or 7½ gallons per sack of cement, depending on whether concrete of 2,900 or 2,000 lbs. per square inch at 28 days was required (American units, etc.).
2. Proportions of cement and aggregate determined solely by the requirements of workability.
3. Quantity of coarse aggregate not less than fine and not more than twice fine.

The following is the actual wording of the Specification :—

"These water-cement ratios [97] are the maximum permissible. The mixes shall be proportioned for somewhat lower ratios, so that with the normal fluctuations, which may be expected from batch to batch, these ratios will not be exceeded. Water or moisture contained in the aggregate must be included in computing the water-cement ratios. Water absorbed by the aggregate in a period of 30 mins. may be deducted in computing the water-cement ratio.

"The water-cement ratios specified shall not be changed except by the Architect. In the event the Architect finds it necessary to change the water-cement ratios from those specified, adjustment, covering amount of cement and aggregates affected, will be made as an extra or a credit under the provisions of the contract.

"The proportions of aggregates to cement for concrete of the water-cement ratios specified shall be such as to produce concrete that can be puddled readily into the corners and angles of the form and around the reinforcement without excessive spading and without undue accumulation of water or laitance on the surface. In no case shall concrete be placed which shows a slump exceeding the following limits :—

For Caissons, ...	Max. slump 4 inches.
For Heavy Walls, Slabs and Beams,	,, ,, 7 inches.
For Thin Walls and Columns, . .	,, ,, 9 inches.

"The proportions of fine and coarse aggregates shall be such that the ratio of the coarse to the fine shall not be less than 1 nor more than 2, nor shall the amount of coarse material be such as to produce harshness in placing or honeycombing in the structure. When forms are removed, the surface and corners of the members shall be smooth and sound throughout."

The specification contains a requirement that the method of measuring moisture in the aggregate shall be such as to give results within 2 lbs. for each 100 lbs. of aggregate ; also a requirement that the aggregate source shall be such that the material received for any one day's operations will be uniform as to quality and grading. It is provided that tests be made during the progress of the work to show the quality of concrete being produced.

Old Specifications.—The older specifications [98] tend to increase the cost of concrete for two reasons :—

1. In general, more cement is used than would be necessary for a given strength if proper limits were placed on the quantity of mixing water. (It was long considered axiomatic that the strength of concrete was a function of the quantity of cement, whereas we now know that it is a function of the water-cement ratio. Rich mixes give better concrete only because of the lowered water-cement ratio.)

2. Aggregates are required to conform to rigid limitations as to size and grading in order that some arbitrary proportions may give the desired strength. As a result, it is frequently necessary to transport aggregates long distances, or to waste certain sizes, thus adding to the cost. By the water-cement ratio method, failure of aggregate to meet the old requirements for size and grading is no longer considered of prime importance, since usual variations can be largely compensated by changes in mix, without sacrificing the strength or quality of the concrete. Almost any two or more fine and coarse aggregates may be combined in such a manner as to give good results.

Consistency.—On outdoor concrete structures,[99] and especially when such structures are heavily reinforced and of considerable vertical depth, the consistency must be controlled within far narrower limits than is now generally done or even advocated. While a predetermined strength may be obtained with concrete showing a wide variation in consistency, every other needed quality of outdoor, heavily-reinforced concrete will be impaired by the use of sloppy concrete, even though the water-cement ratio is maintained. To secure dense concrete of uniform quality throughout its mass, the consistency must be limited to the narrow range between that stiffness at which concrete begins to crumble and that wetness at which concrete begins to segregate. Such consistencies give a concrete that flows readily without separation. Places in which it is difficult or exceptionally expensive to place concrete of this consistency are almost invariably places where the loss of density, the increase in permeability and shrinkage, and the segregation resulting from a sloppy consistency, will

prove serious dangers to the life and strength of a structure. The use of sloppy concrete of whatever water-cement ratio will seriously affect design considerations such as bond and compressive stress at various parts of the structure.

With the same water-cement ratio a medium plastic or medium stiff concrete is superior to a wet or sloppy concrete, because it is denser, heavier and less permeable. There is less diffusion of its particles, produced by water. It is more uniform, and segregates far less in transportation and placing. It shrinks or settles very much less, and grips the reinforcing steel more strongly. It is less subject to damage by freezing and thawing.

Medium stiff concrete presents far less danger of deep or hidden honeycombing, such as would affect the strength of a beam or slab. " Honeycombing " has come to be considered almost entirely as a blemish in surface finish. It is far more than that. Dangerous honeycombing is caused by the mortar separating from the stone in wet concrete and leaving what is really a weakly-cemented stone or gravel pocket. This may or may not show on the surface. With concrete of the consistency advocated, one occasionally finds a surface roughness caused by the failure of the mortar to flow out freely against the forms, and which a slight amount of surface spading would have prevented. But surface roughness of this sort does not materially affect the strength and life of the structure.

Variations.—Abrams' curve (see Fig. 4) refers to typical American cements and gives strengths at 28 days on 12″ × 6″ concrete cylinders cured in a standard manner. These strengths will not be obtained if any of the conditions are different. For instance, appreciable variations are caused by

1. Type of cement,
2. Temperature,
3. Type of aggregate,
4. Type of test specimen, etc.

Some of these items are considered in the following:—

Variation due to Cement.—Tests in this country show that the compressive strength-water ratio relation for a typical

British cement is not the same as that given by Abrams. This point, however, is of small importance, since once the

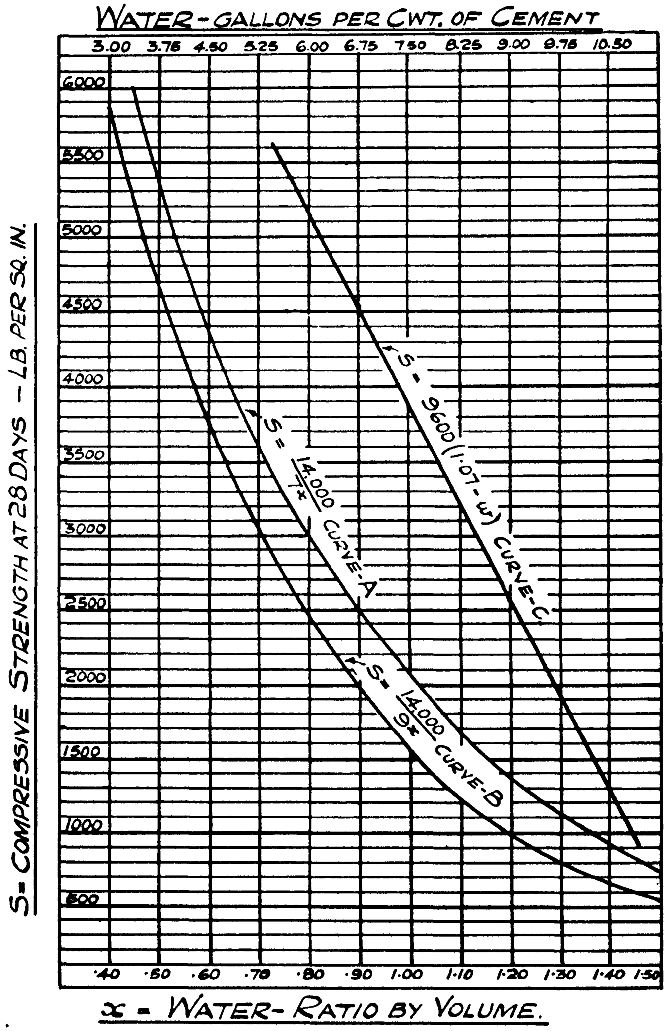

Fig. 4.—Water Ratio Curves.

aggregates and cement have been fixed it is a simple matter to work to a definite curve or formula.

To investigate this, a very limited number of experiments were carried out for the writer with cement "X," using water ratios of 4, 5, 6, 7, 8, 9 and 10 gallons of water per hundredweight of cement. The coarse aggregate was Trent gravel, graded from 1 inch to $\frac{3}{16}$ inch, and the fine aggregate was Trent sand, graded from $\frac{3}{16}$ inch downwards. These were mixed in the proportions of two of coarse to one of fine, by volume. The mixed aggregate was added to the mixture of water and cement (in the proportions given by the water-cement ratio), until a slump of $4\frac{1}{2}$ inches was obtained in each case. Six-inch cubes were made and tested at the age of 28 days, having been kept under standard curing conditions. For this limited range of tests the points plotted were found to lie on a straight line (see Fig. 4), the equation of this curve being

$$S = 9600\ (1{\cdot}07 - w)$$

where S = Compressive stress at 28 days in lbs. per sq. in.
w = Water ratio by weight.

Previous results carried out by an independent investigator indicated that strengths could be found by a curve having the same type of formula as the one obtained by Abrams. In this instance the equation was

$$S = \frac{14{,}000}{5^x}.$$

Both the A and B constants (see p. 169) vary according to circumstances, as has been pointed out by Coultas.[100]

It is just as important to control the water content with aluminous cement as it is with Portland cement. The strength-water ratio relation is similar, and any excess of water beyond that required for workability will result in a corresponding loss of strength.

Comparison of Two Cements.—These variations are too large to be ignored. To appreciate their significance let

us consider a cement which gives strengths according to the equation

$$S_a = \frac{14{,}000}{9^x}$$

and another cement which gives strengths according to the equation

$$S_b = \frac{14{,}000}{4 \cdot 5^x},$$

and let us assume that both these sets of values are those obtained on cylindrical test-pieces. The ratio of the two strengths will be

$$R = \frac{S_b}{S_a} = \frac{9^x}{4 \cdot 5^x},$$

and since x will be constant for a definite water-ratio we have

$$R = \left(\frac{9}{4 \cdot 5}\right)^x = 2^x.$$

For a value of $x = 1$, $R = 2$.
,, ,, ,, $x = \frac{1}{2}$, $R = 1 \cdot 414$.

This means that between these limits of $x = \frac{1}{2}$ and $x = 1$ there is a variation of strength between the two cements of 41 to 100 per cent.

Variation due to Temperature.—A. R. Lord has pointed out that temperature effects [101] may nullify the savings indicated by water-cement considerations in the cooler months, and on the other hand may greatly increase such savings in the summer period. Adequate research to discover the effect of temperature applied in varying degrees and at varying periods in the curing of concrete is needed to clarify the situation. Abrams' fundamental equation is based on a temperature maintained fairly uniform in the curing room during the full test period. The contractor in the field cannot count on this. In temperature changes, which are largely beyond his control, he has to deal with a variable

as great in test influence as water-cement ratio, and as neglected to-day as that ratio was 10 years ago.

Lord found on the Wacker Drive that 1° F. change in temperature was roughly equal to 50 lbs. per square inch change in strength at 28 days. As between the 75° F. average 28-day temperature (July) and the 55° F. (May and Oct.), this means a loss of 1,000 lbs. per square inch. This variation in strength is approximately equal to a change in the water ratio of 1 gallon per hundredweight of cement.

Whilst realising that Lord's data were meagre, the results would give, for the particular conditions,

$$S_{28} = \frac{200\,T}{4^x},$$

where S_{28} = the probable 28-day cylinder strength,
T = the average curing temperature in °F.
x = water ratio by volume.

The curves in Fig. 5 [102] are based on the data given in *Bulletin 81* of the *University of Illinois Experiment Station*, covering tests on concrete cured in a moist atmosphere at various temperatures.

Variation due to Aggregate.—If the only variable is the aggregate, it will be found that instead of obtaining one curve, there will, in general, be a family of related curves, and from these the one should be chosen which gives the required strength and impermeability at the least cost. These curves may be obtained inexpensively on large jobs, and an investigation of this nature will pay for itself many times over. On small jobs it is not usually advisable to consider the matter so closely.

The matter is further complicated by the fact that the relationship between the water-cement ratio and the strength is altered considerably for aluminous cement, and not inconsiderably for Portland cement, by the addition of sand. Hence, the water-cement ratio cannot be considered as the only factor affecting the strength of mortar and concrete. Tests at the *Karlsruhe Concrete and Reinforced Concrete Institute*, Germany,[103] showed that alteration of the grading of the aggregate, from the ideal to a mixture

excessively rich in sand, had the same effect on the compressive strengths as an increase of 0·2 in the water ratio of a good concrete.

Variation due to Test Specimens.—There is always a difference in strength due to the use of different types of test specimens. The (English) 6-inch cube will probably

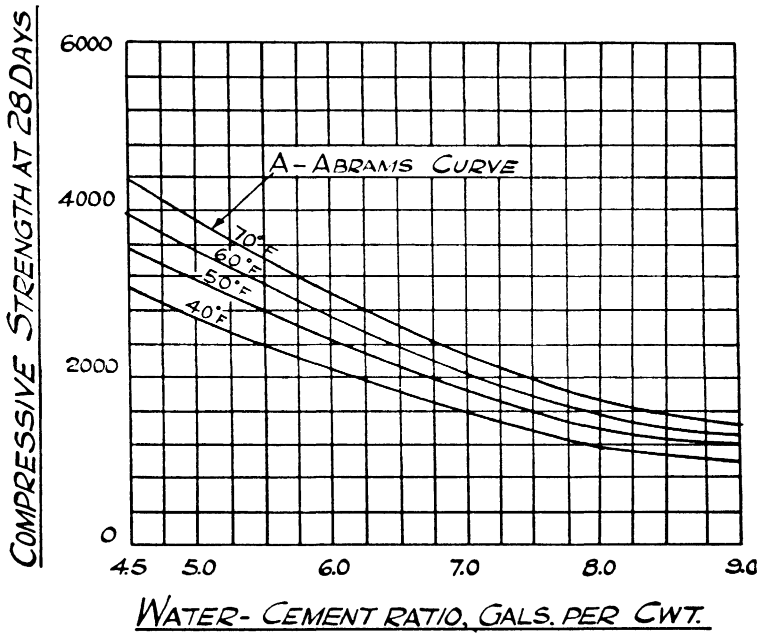

Fig. 5.—Temperature and Water Ratio.

give values 15-20 per cent. higher than the (American) 12″ × 6″ cylinder, made with the same concrete.

Design of Pavement Concrete.

The notes in this section are abstracted from an article [104] in "*Public Roads*," and they are given in somewhat detailed form because :—

1. They represent up-do-date practice.

2. They explain the practical application of design principles.

3. They will serve as a guide for the reader's own investigations.

Important Factors.—Attempts which have been made to design concrete by the application of certain formulae based only on considerations of the grading of aggregates, such as fineness modulus, grading factor, surface area, etc., have failed, at least in so far as concrete for pavements is concerned, in one important respect—they do not take into account the character of the aggregates employed. By character is meant not only type—that is, crushed stone, gravel, etc.—but such factors as surface texture, angularity of fragments, etc. These factors affect the quality of the concrete in two ways—first, by influencing workability, which in turn controls the ratio of fine to coarse aggregate as well as the relative water content, and second, through the adhesion or bond which is produced between the cement and the aggregate surfaces.

The effects of such factors are particularly noticeable when the concrete is subjected to tensile and flexural stresses, and they are therefore of importance to the highway engineer. They apply alike to fine and coarse aggregates, and explain why the experimental or trial method of design must be used.

Ratio of Fine to Coarse Aggregate.—The first question to decide is the proper ratio in which to combine the various fine and coarse aggregates which are available for a given job, giving in each case due consideration to both workability and economy. There are four general rules which may be applied to this particular problem, as follows :—

1. The proportion of sand should be increased as the sand becomes coarser.

2. The proportion of sand should be increased as the maximum size of the coarse aggregate becomes smaller.

3. The proportion of sand should be increased as the percentage of fine material in the coarse aggregate becomes smaller.

4. The proportion of sand should be decreased as the

percentage of fine material in the coarse aggregate becomes larger.

These principles are well known. The average specification for concrete, however, recognises them only in a general way, usually by a clause giving the engineer the power to change slightly the proportion of fine to coarse aggregate to secure maximum density. It should be possible in designing the mix to fix this ratio much more accurately than is possible under the present arbitrary method. The most important point to remember is, that a balance will have to be struck between a high-sanded mix, which, although workable, is apt to be uneconomical (due to the fact that, for a constant water-cement ratio, more cement will be required for a given consistency), and a low-sanded mix, which, although economical in so far as cement content is concerned, is apt to give trouble in placing.

As a guide in making a preliminary estimate of the proper ratio to use in any specific case, the values given in the table on page 182 may be taken. In general, these ratios are about the same as would be obtained by the use of the fineness modulus method, except that in no case is the percentage of fine aggregate less than 25 or more than 45 per cent. of the sum of the volumes of the fine and coarse aggregates measured separately. It will be observed that the values illustrate the principles governing the proper ratio of fine to coarse aggregate just given. The values given in the table do not represent necessarily the final ratios to use. The best final values in any case can only be determined by trial, bearing in mind that the smallest amount of sand consistent with workability should ordinarily be used.

Determination of Proportions.—It will be assumed that the specifications call for a concrete which, when tested under standard laboratory conditions, will have a certain modulus of rupture, say 600 lbs. per square inch at 28 days. The problem is to determine the most economical mixture which will give this strength and at the same time be sufficiently workable to place and finish properly on the job.

APPROXIMATE RATIOS, BY VOLUME, OF FINE TO COARSE AGGREGATE FOR PAVING CONCRETE, MACHINE FINISHED.

Coarse Aggregate Size Limits.	Fine Aggregate Size Limits.			
	0-No.16.	0-No.8.	0-No.4.	0-⅜in.
No. 4 to ¾ inch, . .	35 : 65	37 : 63	40 : 60	45 : 55
No. 4 to 1 inch, . .	30 : 70	32 : 68	35 : 65	40 : 60
No. 4 to 2 inches, . .	25 : 75	27 : 73	30 : 70	35 : 65

Notes :—The above values are based on the use of the usual type of natural sand combined with a coarse aggregate consisting essentially of rounded fragments. With coarse aggregate consisting essentially of angular fragments it may be necessary to increase the percentage of sand slightly over the values above given.

It has been assumed that the concrete will be machine finished. For hand-finished work the percentage of sand may have to be increased somewhat.

For an aggregate to be assigned a certain maximum size, at least 15 per cent. must be retained on the next smaller sieve shown in the table. For instance, a sand having 16 per cent. retained on a No. 8 sieve is classed as a 0-No.4 sand. For a sand to be classed as a 0-No.16 sand, at least 15 per cent. must be retained on a No. 30 sieve.

All coarse aggregates are assumed to be reasonably well graded from the maximum size to No. 4, with not more than 15 per cent. passing the No. 4 sieve.

The use of a 0-No.16 sand is not recommended, except under conditions where a coarser sand is not available, on account of the fact that concrete in which a fine sand is used is in general not quite so resistant to wear as when a coarse sand is used.

In trial determinations it will be necessary to use a cement which corresponds to about the lowest-strength cement likely to be used on the job. The use in construction of any higher-strength cement than this simply serves to provide an additional factor of safety, in so far as the cement is concerned. Having selected the cement, it will be necessary to fix experimentally the relation between the water-cement ratio and the flexural strength, using stock aggregates of known satisfactory quality. The

determination of the strength developed at 28 days with water-cement ratios 0·6, 0·7, 0·8, 0·9 and 1·0 (by volume) will usually give enough points from which to plot this relation. Such a relation for an assumed case is shown in Fig. 6. It will be observed that a ratio of 0·7 gives a strength of approximately 600 pounds per square inch.

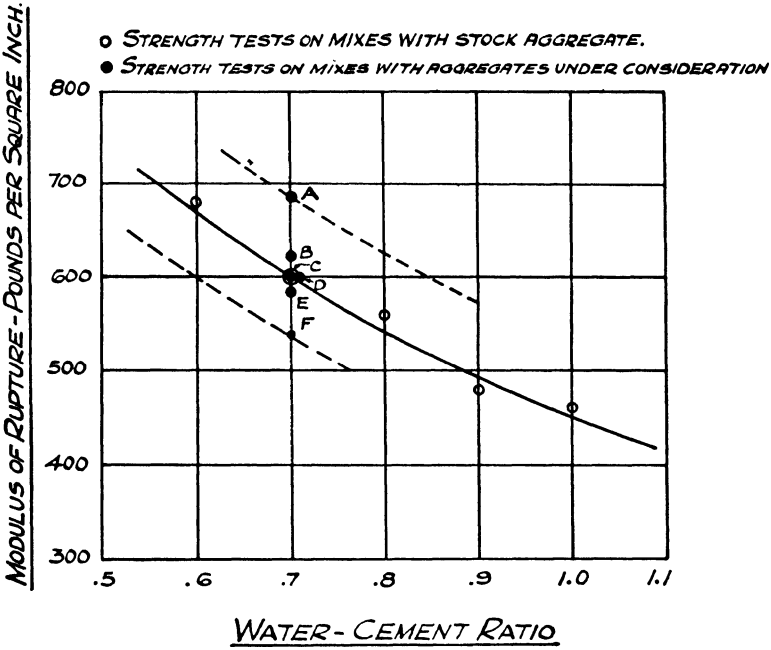

Fig. 6.—Water Ratio and Flexural Strength.

The next step is to make up concrete specimens with each of the aggregate combinations, using 0·7 water-cement ratio and the consistency which will be used on the job. It is important in this experiment to maintain the consistency as nearly constant as possible. With a constant water-cement ratio this will necessitate variable proportions, depending upon the type and gradation of the materials. The proper amount of cement to use in each case must be obtained by trial, adding small quantities of the aggregates

in question to the cement paste until the proper consistency has been reached. The predetermined ratio between fine and coarse aggregate must be maintained throughout the operation. From the final quantities used the proportions either by weight or by volume may readily be calculated. Let us assume that the following strengths were actually obtained on six combinations of material :—

Combination.	Modulus of Rupture in pounds per sq. in.	Combination.	Modulus of Rupture in pounds per sq. in.
A.	670	D.	600
B.	625	E.	580
C.	600	F.	535

These values are plotted in Fig. 6. It is observed at once that four of the six combinations give strengths either identical or practically identical with the basic or standard laboratory combination. There are, however, two outstanding exceptions, one much higher and one much lower. These two combinations, A and F, will be used as the basis for further discussion.

It is now assumed that had curves been developed for the relation between water-cement ratio and strength for these combinations, as was done for the basic mix, these curves would have been substantially parallel to the basic curve over the comparatively narrow range in which we are interested. This may or may not be absolutely correct, but it is believed that for the range of mixtures covered by paving concrete it is substantially true. Granting this, we can omit the actual determination of this relationship for any of the combinations in which we are interested and simply draw through the value which we have plotted a line parallel to the basic curve. This has been done in Fig. 6 for combinations A and F. To determine the water-cement ratio to use with either of these combinations to obtain a strength of 600 pounds, simply follow the curve representing the material either to the right or left, as the

case may be, until it intersects the 600-pound line and use the corresponding water-cement ratio. Fig. 6 shows this to be 0·85 for combination A and 0·60 for combination F. A choice between these combinations will depend entirely on which is the cheaper, all things considered, always assuming that the aggregates in both cases are structurally sound and have sufficient resistance to wear.

Before the cost can be determined it will be necessary to determine by trial the proportions required in these two cases to give the consistency required at the water-cement ratios indicated—that is, 0·85 for combination A and 0·60 for combination F. Assume, for purposes of illustration, that the proportions for combination A with a 0·85 water-cement ratio reduce to 1 : 2 : 4 by volume and that the proportions for combination F with a 0·60 water-cement ratio reduce to 1 : $1\frac{1}{2}$: 3. Which of the two is the cheaper will, of course, depend almost entirely on the relative costs of the aggregates delivered on the job.

Effect on Specifications.—In using this method of designing concrete mixtures in actual construction, it will be necessary to change the present method of specifying arbitrary proportions to a specification based on a certain required minimum strength. Such a revised method of specifying has recently been suggested by J. T. Voshell.

Each contractor, instead of specifying a price per square yard for concrete in place, would be required to submit separate tenders for all materials which he is prepared to furnish, together with a separate price per square yard for mixing, placing, finishing and curing the concrete in accordance with the requirements of the specification. After receipt of proposals, the engineer would examine all of the sources proposed, first, with the view of eliminating any which do not comply with the basic requirements of the specifications, and second, to determine which of the materials proposed will produce concrete of the required quality at the lowest cost. The job should be let to the contractor who can supply the materials, and mix and place the concrete, at the lowest total price per square yard.

With this procedure the responsibility for selecting the materials and adjusting the mix to secure concrete of the

desired quality, as well as the responsibility of seeing that the production of the concrete is carried out in accordance with the specifications, rests solely with the engineer. This is as it should be, unless we are prepared to go to the other extreme and specify the quality of the finished concrete and allow the contractor to use any materials and methods of production he desires so long as he fulfils this requirement. This latter alternative would not seem feasible at present.

High Early Strength.

Importance of Early Strength.—During recent years efforts have been made to speed up the hardening of concrete, and the most obvious results are seen in the large number of rapid-hardening cements now on the market. But it is often overlooked that appreciable gains in early strength may be obtained without these cements. There are engineers who, rightly or wrongly, distrust these "new" cements from the point of view of their long-date strengths, and for such, at least, the methods of obtaining high early strength with ordinary cements will be of interest. It is not suggested that ordinary cements can do the work of rapid-hardening cements in every respect, but their possibilities have been rather overshadowed by the campaign on behalf of the rapid-hardening varieties.

Using Ordinary Portland Cement.—With ordinary Portland cement, early hardening may be obtained by :—

1. Lowering the water-cement ratio by
   - (*a*) Decreasing the water content.
   - (*b*) Increasing the cement content.

2. Mixing under better conditions by
   - (*a*) Increasing time of mix.
   - (*b*) Raising temperature of mix.

3. Using a suitable admixture.

4. Curing under better conditions by
   (*a*) Keeping concrete wet.
   (*b*) Raising temperature of concrete.

Water Ratio.—As already shown, the strength of concrete depends essentially on the value of the water-cement ratio. For an ordinary mix, a 1 per cent. increase in the water content may reduce the two-day strength by 2 per cent. In one instance—see table on page 188—when the water was reduced from 7·7 gallons to 6·1 gallons per hundredweight of cement, the three-day strength was increased from 750 lbs. to 1,350 lbs. per square inch. There is a practical limit to the decrease of the water content, since the concrete must be workable ; so that beyond a certain point a reduction in the water content must be accompanied by a corresponding reduction of the aggregate content. In effect, we get a richer mix. For high early strength, rich mixes, having a low water ratio, are essential.

Mixing.—More attention must be paid to the mixing, particularly as drier mixes are being used. In general, there is an increase of strength at all ages for increasing periods up to five minutes ; but as this is too long for most practical conditions, a two-minute period might be worked to with advantage. Although it may not be convenient to alter the temperature of the mix, it is advisable to remember, particularly in cold weather, that the warmer the concrete, the sooner it sets and hardens.

Admixtures.—Admixtures may be used simply to increase the workability of the mix, and so assist in the reduction of the water ratio. For instance, hydrated lime may be used, but it must not be added *ad lib.* An upper limit should be fixed at, say, 10 per cent. of the cement (by weight).

Some admixtures definitely increase the early strength of the concrete and also reduce the setting period. Such materials, when used discriminately, are clearly of value ; many of those sold as proprietary articles are perfectly safe. Note that the influence of an admixture may vary with different cements.

Curing.—Correct curing means not only high early

HIGH EARLY STRENGTHS.

Ref.	Mix.	Galls. Water per Cwt. of Cement.	Approx. Slump, Inches.	Lbs. Admixture per Cubic Foot Cement.	Minutes Mixing Time.	Compressive Strengths, lbs. per square inch.			
						1 Day.	3 Days.	7 Days.	28 Days.
A	1 : 2½ : 4	7·7	6 to 7	0	1	240	750	1,320	2,600
B	1 : 2½ : 4	7·7	6 to 7	0	5	340	910	1,550	3,030
C	1 : 2½ : 4	6·1	½ to 1	0	1	520	1,350	2,090	3,700
D	1 : 1½ : 2½	5·5	6 to 7	0	1	560	1,580	2,530	4,230
E	1 : 1½ : 2½	4·4	½ to 1	0	1	880	2,410	3,630	5,250
F	1 : 1½ : 2½	4·4	1	0	5	1,150	2,860	4,020	5,740
G	1 : 1½ : 2½	5·5	6 to 7	2	1	930	1,880	2,610	3,800
H	1 : 1½ : 2½	3·4	0 (dry)	2	5	1,910	3,380	4,200	5,260

strength, but better concrete in every way. Concrete kept wet after setting will, in the early stages, be as much as 50 per cent. stronger than similar concrete allowed to dry-out immediately. Here, again, the warmer the better, and in cold weather an effort should be made to cure the concrete under conditions such that the temperature never falls below 70° F.

Summary.—It should not be overlooked that of the ordinary cements available, some are much better than others, and the best should be chosen for high early strength work. The table [105] on page 188, compiled for "*Universal*" Portland cement (U.S.A.), shows how high early strengths may be obtained in various ways.

It will be observed that, although the admixture used gave higher early strengths, the 28-day strength was higher in the batch where there was no admixture.

In brief, high early strength concrete may be obtained with ordinary Portland cement by :—

1. Choosing a good cement.
2. Using a rich mix and a low water ratio.
3. Mixing for at least two minutes at as high a temperature as practicable.
4. Curing thoroughly at as high a temperature as practicable.
5. Using a suitable admixture.

All these taken together will show surprising results.

Approximate Quantities.

Water.—A practical man often asks how much water he should use in a concrete mix. A consideration of the foregoing pages indicates that it is not possible to give a definite answer without carrying out careful experiments, but an approximate method which has been suggested for determining the amount of water for dry and non-absorptive materials is to take 28 per cent. of the weight of cement plus 4 per cent. of the weight of the total aggregate. Allowance would have to be made for absorption by

aggregates and for water in aggregates. The following table may also be used as a rough guide.

WATER FOR CONCRETE.				
Mix.			Gallons Water per Cwt. Cement.	
Coarse Aggregate.	Fine Aggregate.	Cement.	Minimum.	Maximum.
6	3	1	8¼	8¾
5	2½	1	7¼	7¾
4	2	1	6	6½
3	2	1	5¾	6¼
3	1½	1	5½	6
2½	1¼	1	5	5½

Water for Hydration.—Portland cement contains about 65 per cent. of lime. 56 lbs. of lime require 18 lbs. of water for complete hydration, so that 100 lbs. of cement require

$$\frac{65 \times 18}{56} = 20{\cdot}9 \text{ lbs. water.}$$

It is not certain that all the lime becomes completely hydrated, so that in practice the amount of combined water will be less than this. For concrete cured under water a typical value is 14 per cent.

CHAPTER X.

PROPORTIONS.

METHODS OF PROPORTIONING.

WHILE the writer feels that the question of proportioning concrete should be based on the water-ratio theory, the method is not sufficiently well known in this country to supplant prevailing practice. The usual method is to use arbitrary volume proportions, but this has little to recommend it for continued use, and it is suggested that we can get a little nearer to the ideal by altering our way of stating the proportions, so that there will be less variation in the different batches of concrete than formerly.

Methods of Measuring Constituents.—Each of the three constituents—cement, fine aggregate, and coarse aggregate—may be measured separately by volume or by weight, so that already we have eight possible variations. Again, the aggregates may be mixed in predetermined proportions, and then measured together by volume or by weight, thus giving four more possibilities. A different treatment entirely is to state the volume or weight of cement per unit volume of finished concrete, giving two more ways. Finally, the fine material may be measured by inundation, and then combined with certain volumes or weights of cement and coarse aggregate.

It is not necessary or desirable to consider each possible set of conditions, and it is proposed to deal with the various factors so as to eliminate several of the combinations in a rational manner.

Measuring Cement.—As already stated, cement may be measured by volume or weight. Perhaps the oldest method is that of specifying the number of bushels of cement to be mixed with certain amounts of fine and coarse aggregate. This method is seen in its most precise form when the

amount of cement is specified in "striked bushels," but it need only be mentioned to be dismissed as a lagging survival.

A slightly more modern method is to specify the cement by cubic feet. For instance, a 4 : 2 : 1 concrete would be understood to mean a concrete composed of 4 volumes (say cubic feet) of coarse aggregate, 2 volumes of fine aggregate, and 1 volume of cement. This method is only a little better than the "striked bushel" method, since the weight of cement in a cubic foot is a very variable amount, depending on the degree of consolidation and the fineness of the grinding during manufacture. Further, cement is not sold by volume.

Clearly, then, cement should be specified by weight. There is no objection, of course, to changing a 4 : 2 : 1 volume specification so that the cement is actually measured on the job by weight, though it is better to have the original specification altered. If this change is made, consideration should be given to the kind of cement used. If the cement just passes the requirements of the British Standard Specification, then a value of 90 lbs. per cubic foot may be used. If, on the other hand, a more finely ground cement, such as "*Ferrocrete*," be used, the weight per cubic foot may be reduced to 80 lbs.

To carry the process a stage further, the cement may be specified in bags, since a known weight will be in every bag. An objection to this is that a torn bag, which has lost some of its contents, may be treated as a whole bag. This kind of thing can be prevented only by adequate supervision.

Measuring Aggregates.—Coarse aggregate may be measured by volume or by weight. The latter method is, perhaps, more accurate, though measurement by volume is quite serviceable if consideration is given to the method used. In either case the water content should be determined and allowed for in some suitable manner.

The question of dealing with the fine aggregate is more difficult, on account of the bulking that takes place, due to the presence of moisture. If a small amount of water, say 5 per cent. by weight, is added to dry sand, the volume of the sand is increased out of all proportion to the amount of water used. Therefore, one cubic foot of the moist sand

will weigh less than one cubic foot of the dry sand; or, put in another way, there will be less actual aggregate in a cubic foot of the moist sand than in a cubic foot of the dry sand. The bulking effect can be allowed for in various ways, as follows :—

(1) Proportioning by volume. This is done after making a correction for the bulking of the sand.

This method is hardly likely to produce a uniform concrete of specified strength without the most stringent field control,

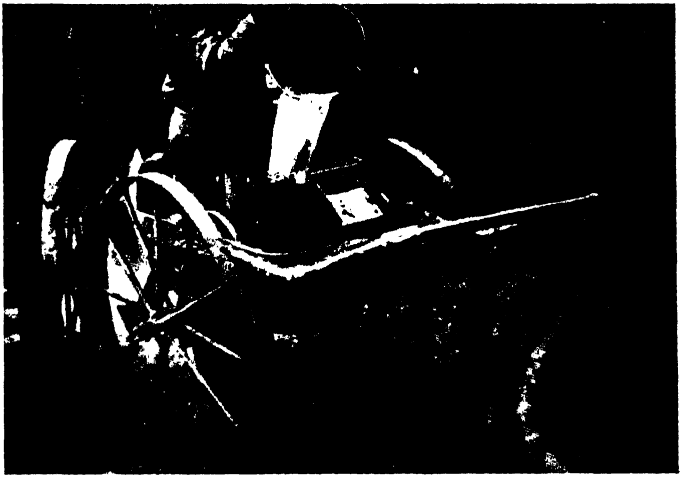

Fig. 7.—Charging "Junior" Inundator with Water.

and it appears to be the method of the past rather than of the future.

(2) Proportioning by weight. This is done after making allowance for the weight of moisture present in the sand.

When the proportions are measured by weight the evil effects of loose volumetric measurement and bulking are eliminated, and it is necessary only to make allowance for the moisture present.

(3) Removing the moisture in the sand by heating. Then the proportions can be by volume or by weight.

It has been suggested that the effects of moisture can be

eliminated by having the aggregates mechanically dried. This method has several inherent objections, but it is significant that such a suggestion has been seriously considered at all. A more rational scheme would be to attempt to use the water present, since it will actually be required in the concrete ; this can be done when the inundation method is adopted.

(4) Inundation.

In this method the sand is flooded with water in a vessel of known capacity, so that every time the vessel is filled with sand after being filled with water, some of the water is displaced, and a known quantity of sand and a known amount of water are obtained. This method has proved highly satisfactory in practice, and quite inexpensive apparatus can be purchased for small jobs (see Fig. 7).

Variations in Aggregate Proportions.—The following table [106] shows how the addition of fine material stiffens the mix of fixed water-cement ratio concrete more than corresponding additions of coarse aggregate. These data are from actual tests using sand and gravel aggregate, the mixes indicated being on the basis of dry, compact volumes (U.S.A. values).

Mix, Dry Compact Volumes, Cubic Feet.	Water-Cement Ratio, U.S. Gallons per Sack.	Yield, Cubic Feet Concrete from 1 Sack Cement.	Slump, Inches.
1 : 1½ : 3	5¾	3·6	9·3
1 : 2½ : 3	5¾	5·0	0·5
1 : 1½ : 4	5¾	4·9	4·5
1 : 3 : 0	6	3·4	0·8
1 : 2 : 3	6½	4·7	7·8
1 : 3 : 3	6½	5·7	0·6
1 : 2 : 4	6½	5·4	6·0

The table shows that adding 1 cubic foot of sand to the 1 : 1½ : 3 mix to obtain the 1 : 2½ : 3 mix reduces the slump from 9·3 inches to 0·5 inch, while adding 1 cubic foot of coarse aggregate to obtain the 1 : 1½ : 4 reduces the slump only to 4·5 inches. Similarly, in the second group of mixes, for a water-cement ratio of 6½ gallons per sack, the extra

cubic foot of sand has a much greater effect than has the extra cubic foot of coarse aggregate. The all-sand mix (1 : 3 : 0) in the first group shows a very stiff consistency and a very low yield.

Weighing Aggregate.—As a result of experience in weighing concrete aggregates on paving contracts in Iowa, it was reported [107] that

1. The method entails no added cost.
2. No loss in time or decreased production occurs.
3. Weighing is a more accurate way of measuring granular materials than loose volumetric measurements.
4. A valuable record of the amounts of materials used is secured.
5. Corrections for moisture content can easily and frequently be made.

Inundation.—The following conclusions regarding the practical use of the inundation method were submitted in 1923 [108] :—

1. The results of the tests indicated that when sand is measured in water the quantity of sand per unit of volume is almost constant, regardless of the original water content of the sand, and that the water filling the voids in the sand is also nearly constant for any given method of placing the sand.

2. The shovelling of the sand into the water gave more nearly constant quantities of sand and of water per unit of volume than any of the other methods used.

3. The screening methods gave slightly larger quantities of sand and slightly smaller quantities of water per unit volume than did the shovelling method and the results of the tests indicated a lower percentage of air voids for this method of placing the sand than for either the shovelling or the rodding method.

4. The rodding of the sand in water gave a larger quantity of sand per unit of volume than any of the other methods used.

5. The indication was that the measurement of sand by inundation methods should be of assistance in reducing

variability of strength of concrete caused by variations in quantities of sand and water in a batch.

The use of a constant water-cement ratio for the concrete, together with a constant fineness modulus for the mixed aggregate, resulted in nearly a constant strength, regardless of the proportion of fine to coarse aggregate in the mix.

6. The use of a constant fineness modulus of the mixed aggregate did not result in a constant slump or flow for the concrete. The variation in each was approximately proportional to the variation in the fineness modulus of the fine aggregate in the mix.

7. The weight of the concrete per cubic foot, and the volume yield of concrete per barrel of cement, were practically constant.

Summary.—In conclusion, it is suggested that the best methods to adopt are

1. Measuring the cement by weight.

2. Measuring the fine aggregate by the inundation method, or by weight (allowing for the water content).

3. Measuring the coarse aggregate by weight and allowing for the water content.

4. Measuring by weight or by volume the remaining quantity of water necessary to give the desired water-cement ratio.

MOISTURE IN AGGREGATES.

Variation in Quantity of Water in Mix.—Having decided on the quantity of water to use it is necessary to devise means by which we can be assured that there are no variations. Variations may be caused by :—

(1) Improper measurement of the added water.

(2) Ignoring moisture present in aggregates.

(3) Absorption of water by dry or partially dry aggregates.

(4) Loss of water from, or addition of water to, batch during transportation, placing, and whilst in position before setting.

Of these (1) and (4) may be adjusted by careful workmanship, but (2) and (3) require investigation. As far as (3) is

concerned, it is clear that water which is absorbed by an aggregate should not be included in the quantity allowed in mixing the concrete, since, as it is absorbed by the aggregate, it will not be reacting with the cement during the setting and hardening. The free moisture present in the aggregates may be allowed for by assuming an arbitrary figure which, after a fair amount of practice, should not be far wrong, or by actual measurement. This quantity should be subtracted from that specified to find the amount of water to be added.

Determining Moisture in Sands.—For determining moisture in sand it is necessary to adopt some quick and accurate method suitable for job conditions. Several methods are now being used, and to study their advantages and disadvantages an investigation was undertaken and reported in the *Proceedings* of the *American Concrete Institute*, 1929.[109]

The following methods of determining moisture in sand were compared :—

1. Use of electric resistance moisture meter.
2. Drying to constant weight in oven.
3. Drying to constant weight with denatured alcohol.
4. Displacement method using cylindrical container.
5. Displacement method using A.S.T.M. flask.
6. Specific gravity method using salt solution hydrometer.

Of the methods now in use probably the most common is that in which a definite weight of damp sand is dried to a constant weight and the difference in weight between the wet and dry sample is used in determining the actual moisture in the sand, including that absorbed by the aggregate. Drying by burning-off alcohol and the water from the damp sand is a variation of this method.

The displacement method consists essentially in finding the difference in amount of water displaced by a damp sample and a dry sample of the same weight. Two of the methods are of this type. The method at first appears more simple than the drying methods, but more manipulations

are required in making the determination, and the chance of error is increased.

The specific gravity method is based on determining the specific gravity of a concentrated salt solution to which the damp aggregate has been added. The salt solution is diluted in proportion to the moisture content of the aggregate. Here again the number of separate manipulations required in making a determination increases the chance of error.

The moisture meter or electrical method is for use primarily in determining the relative moisture contents of fine sands used in foundry work. The principle upon which this meter works is the difference in resistance offered to an electric current by varying percentages of moisture with sand; the greater the moisture content, the less the resistance. In using this method it was found that a change in the grading of the sand acted in the same way as a change in moisture content, and thus limited the accuracy of the method.

Discussion of Tests.—Following is a brief discussion of each of the methods used :—

(1) *Electric Resistance Moisture Meter.*—This apparatus was manufactured for testing the relative moisture contents of foundry sands, but was found not to be well suited for testing the coarser sands used in concrete construction. While it was the quickest method used, the results were not accurate.

The readings were not given in per cent. moisture, but as relative moisture. It would, therefore, be necessary to plot curves showing the relation between the actual moisture content and the moisture meter reading. This relation would vary for each type and grading of sand.

(2) *Drying to Constant Weight in Oven.*—This method was one of the two most accurate methods used. Its principal limitations are the necessity of a stove or drying device of some kind, and the necessity of determining the absorption of an aggregate in order to calculate the free moisture contained in the sample.

(3) *Drying to Constant Weight with Denatured Alcohol.*—This method, from the standpoint of simplicity, accuracy

and speed, was probably the best of the six methods tried. Its one limitation was the necessity of determining the absorption of an aggregate in order to obtain the free moisture content.

(4) *Displacement Method Using Cylindrical Container.*—The results obtained by this method were not as accurate as those obtained by the two methods of drying to constant weight, but ranked third in point of accuracy. The advantage of this method over the drying-out methods was that the percentage of moisture obtained was the free moisture, thereby eliminating a correction for absorption. Its advantage over the A.S.T.M. flask was the ability to read more accurately, due to the scum not collecting in the water gauge, as was the case with the flask.

(5) *Displacement Method Using A.S.T.M. Flask.*—The results obtained by this method were not as accurate as hoped for. The principal trouble encountered was the inability to read the water displacement accurately, due to the scum which collected on the top of the water in the neck of the flask. In order that comparable tests could be made, the flask was read at the line of demarcation between the water and the scum. The wet sands collected more scum than the drier ones; this probably explains the greater inaccuracies obtained with the wetter samples.

(6) *Specific Gravity Method Using Salt Solution Hydrometer.*—This method gave the most inaccurate results of the five (not including moisture meter) compared. The hydrometer was not sensitive enough to be read closely. It is quite possible, however, that by reducing the range and increasing the length of the instrument it could have been made to be read more accurately. The maximum range of the hydrometer used was from 0 to 3·5 gallons per 100 lbs. of wet sand. This could easily have been reduced to 2 gallons of water per 100 lbs. of aggregate without sacrificing usefulness for concrete sands.

It was necessary to check the density of the salt solution at frequent intervals in order to maintain a solution which gave the required density.

Comments.—It will be seen that the best results were obtained from those methods requiring the simplest

manipulation, and it is thought advisable to describe the following methods in detail :—

(1) Drying to constant weight with denatured alcohol.
(2) Displacement method with cylindrical container.

These are the two methods given in "Concrete Primer," *Proceedings of the American Concrete Institute, 1928*, from which the following descriptions have been taken.

"*Drying to Constant Weight.*—The apparatus required consists of a balance, a 12″ × 8″ × 2″ metal bread pan, a $\frac{3}{8}$″ steel rod about 18″ long, and a $\frac{1}{2}$-pint cup and some denatured or wood alcohol.

"This method is the same as drying over a stove or open fire, but is much quicker and fully as accurate. Place 500 grammes of damp sand in the bread pan. Pour one-third cupful of alcohol over the sand ; stir the mixture with the rod and then spread in a thin layer over the bottom of the pan. Ignite the alcohol and allow it to burn until consumed, stirring the sand with the iron rod during burning. If the sand be excessively damp, it is advisable to repeat the burning process in order to ensure complete drying of the sample. After burning, allow the sand to cool for 2 or 3 minutes and then weigh. The total percentage, p, of moisture may then be calculated from the following formula :

$$p = 100\left(\frac{W - W'}{W'}\right)$$

where p = percentage of moisture by weight of dry sample, including absorbed moisture,

W = weight of damp sample,

W' = weight of dry sample.

"To determine the free moisture, it is necessary to know the percentage of moisture absorbed by the sand. This varies only slightly for different sands and may be assumed as 1 to $1\frac{1}{2}$ per cent. A rough check on the absorbed water

may be made by drying to constant weight a surface-dry sample which had previously been immersed in water for a period of 24 hours. The surface moisture is then equal to the total moisture, p, minus the absorbed moisture.

"*Displacement Method.*—The apparatus consists of a balance sensitive to 1 gramme, a cylindrical container with gauge glass and scale calibrated to read to 5 c.c., 3 feet of spring wire coiled at one end, and an 8-inch funnel with bottom diameter about $1\frac{1}{2}$ or 2 inches. Fill cylindrical container with water up to zero mark on gauge, insert wire into container, allowing coiled end to rest on bottom. Pour a 2,000-gramme sample of dry sand through funnel into container and gradually withdraw wire, agitating the sand while so doing. Read the volume of water displaced. Repeat the operation using the same weight (2,000 grammes) of the damp sand, whose moisture content is to be determined. The percentage of moisture may then be calculated from the formula :

$$p = 100\left(\frac{D - C}{W - D}\right)$$

where p = percentage of moisture by weight of surface dry sample exclusive of absorbed moisture.

D = weight of water displaced by damp sand of weight W,

C = weight of water displaced by dry sample of weight W,

W = weight of sample (dry, surface dry, or damp) (2,000 grammes).

"It is necessary to use a dry sample to establish the constant C. If the specific gravity of the sand changes it will be necessary to make a new determination on a dry sample. The advantage of this method is that if the determination on the dry sample is made quickly, the result gives the free or surface moisture directly, thus requiring no correction for absorbed moisture."

QUANTITIES.

1 cubic foot of loose Portland cement will make about

4·1	cubic feet of concrete mixed	1 : 2 : 4
5·0	,, ,, ,, ,, ,,	1 : 2½ : 5
5·8	,, ,, ,, ,, ,,	1 : 3 : 6
7·5	,, ,, ,, ,, ,,	1 : 4 : 8

MATERIALS FOR 1 CUBIC YARD OF CONCRETE.

Based on loose cement weighing 90 lbs. per cubic foot and a cubic foot of loose, moist, coarse sand weighing 89 lbs. when dried.

Proportions.	Kind of Coarse Material.	Lbs. Portland Cement.	Sand, Cubic Yard.	Coarse Material, Cubic Yard.
1 : 1 : 2	Shingle (40 per cent. voids),	869	0·36	0·71
,,	Broken stone (45 per cent. voids),	902	0·37	0·74
1 : 1½ : 3	Shingle,	666	0·41	0·82
,,	Broken stone,	697	0·43	0·86
1 : 1⅔ : 3⅓	Shingle,	610	0·42	0·84
,,	Broken stone,	640	0·44	0·88
1 : 2 : 4	Shingle,	520	0·43	0·86
,,	Broken stone,	548	0·45	0·90
1 : 2½ : 5	Shingle,	430	0·44	0·88
,,	Broken stone,	450	0·46	0·92
1 : 3 : 6	Shingle,	364	0·45	0·90
,,	Broken stone,	383	0·47	0·94
1 : 4 : 8	Shingle,	280	0·46	0·92
,,	Broken stone,	294	0·48	0·97

CHAPTER XI.

MIXING AND PLACING.

Mixing.

Mixing appears so simple, and is made so easy by the modern mechanical mixer, that too little attention often is paid to this essential operation. The utmost care in choice of ingredients and in placing of the concrete will be of little avail unless thorough mixing ensures a homogeneous material.

On warm days it may be necessary to allow a little more mixing water to keep the required water ratio in the concrete when it is in the forms. Similarly, a mixer some distance from the place of final deposit may need more water than one close at hand.

Good Mixing a Benefit to Contractor.—The assurance [110] of stronger concrete with thorough mixing operates to the advantage of the contractor, especially when he is working under the water-cement ratio specifications in which concrete of certain definite strengths is the principal requirement. The fact that thorough mixing also makes much more uniform concrete is of interest to the contractor. Specimens of concrete mixed for only fifteen seconds showed an average variation in strength of 30 per cent., while specimens made of concrete mixed for two minutes varied only 10 per cent.

Workability is also increased by longer mixing, and this quality has a definite bearing on the cost of placing the concrete. Concretors who have lengthened their mixing time have found that not only did they place better concrete than ever before, but the concrete was easier to handle, and the total time required for the job was not increased.

When mixer output is speeded up by cutting down mixing

time, the gain to the job as a whole is not as great as is sometimes expected. The spurt is usually followed by a period when the mixer is idle while materials are being measured and placed in the skip. Studies made by contractors themselves have shown that the best way to increase mixer output is to cut down the idle time when the mixer is not operating between batches.

Hand-Mixing.[111]—When small quantities only are used at irregular intervals, such as is often the case when a builder makes a few concrete articles as a side-line, hand mixing may be the most economical method.

If the materials are mixed by hand the mixing should never be done on the ground, as it is practically impossible to prevent earth being scraped up and turned in with the other materials. For indoor mixing a concrete floor is best, and will be found cheaper than wood, owing to its longer life. If the mixing is done out of doors, a wooden platform of boards securely battened together should always be used, and this should be close-jointed, in order that none of the water may be lost. For the same reason the platform should be perfectly level, so that the water will not drain off.

In order to get a thorough mix, the cement and aggregate should be measured on to the platform and turned over dry until the colour is uniform. The water should then be added, and the whole turned over at least three times, or until a thorough mix is obtained. The water should be sprinkled on through a rose, and not thrown on from a pail, as the latter method will wash the cement from the aggregate and nullify the effect of the previous dry mixing.

Machine Mixing.—Machine mixing is preferable, being more thorough and giving more uniform results, and in most cases it will be found cheaper than hand mixing. Efficient mixers may be bought from £20, so that the initial outlay is quite small. Most mixers are portable, and may be transferred readily on their own wheels from one job to another.

Up-to-date models of the larger mixers are fitted with automatic water supply, by which the amount of water pre-determined upon as correct is controlled by the machine.

On some of the latest types of machines the period of mixing is also controlled automatically.

The usual practice is to put the cement and aggregates in the drum, and mix them until they are of uniform colour, then add the water (while the drum is still revolving) and continue mixing until every particle is completely wetted.

If the machine is not fitted with a tank and water measuring device, an ordinary flushing tank which will deliver the same quantity for each batch makes a good substitute. For preference the water should be led into the drum through a perforated pipe, to distribute it evenly over as much of the contents as possible.

The best results are obtained by adhering to the manufacturers' recommendations as regards speed of rotation; any attempt to increase output by increasing the r.p.m. is likely to result in loss of concrete strength. The same applies, to a large extent, to the designed capacity of the mixers. Maximum output is best obtained by careful adjustment of the times required for filling, mixing and emptying. The mixing action is affected by: Blade arrangement, speed, overloading, and roughness of mixer surfaces.

Time of Mixing.—Several years ago the obviously inadequate mixing periods allowed on many concrete jobs led to the making of careful investigations. The *American Portland Cement Association* advocated a period for mixing of not less than one minute, and this was a reasonable conclusion from the data they submitted. They found that mixing up to five minutes increased the strength in all cases, and in some cases mixing for much longer periods caused further increases in strength.

More recently the *U.S. Bureau of Public Roads* has investigated the problem on various road jobs throughout their country. From their results it would appear that on actual road jobs a mixing period of 45 seconds gives practically as good a result as a period of 90 seconds. It is unwise, however, to work to this limit, and to allow a safety factor it is suggested that the minimum mixing time be fixed at one minute. Recent investigations in this country and on the Continent show agreement.

It should always be remembered that if the mixing period be cut down by one half, there is a risk of unsatisfactory concrete being made, whereas, if the mixing period be doubled, the only disadvantage is that which may be caused by the time factor.

Central Mixing.—During the last few years [112] central mixing plants have come into extended use in the larger cities of the U.S.A., where the demand for concrete for construction purposes is sufficient to permit economical operation. As a rule, adequate equipment is provided for the rigid control of the proportioning of the materials, the amount of water used, and the time of mixing. On account of the large output it is possible, at a nominal expense per yard, to supervise all operations in order to ensure the best results. It has been found that by careful proportioning, concrete may be transported for long distances without segregation.

At present it is felt that the time interval between mixing and placing should not exceed 30 minutes, even though tests indicate no appreciable reduction of strength where the interval was as much as two hours.

In order to increase the radius of operations, many of the central mixing plants have installed agitators in the delivery trucks to reduce the tendency to segregation.

There has also been developed the mixing truck, which is nothing more than a mixer mounted on a truck. The cement and fine and coarse aggregates are placed in the mixing truck and the water is carried in a separate tank. A few minutes before the truck arrives at the job the mixer is started and water added so that the concrete is mixed and ready to be dumped into the forms immediately on its arrival at the job.

By the use of concrete from a properly controlled central mixing plant, it is possible to secure on the smallest job the same refinement of design and control as is secured on the large job.

Suggested Specification for Mixing Concrete.

Machine Mixing.—The concrete shall be mixed in a batch mixer. The capacity of the drum shall be such that

only whole bags of cement are used in each batch. Mixing shall continue for at least 1 minute after all materials, including water, have been placed in the drum, and before any part of the batch is discharged. The drum shall be revolved at not less than 14 or more than 18 revolutions per minute. The drum shall be emptied completely before receiving materials for the succeeding batch. The volume of the mixed material in each batch shall not exceed the mixer manufacturer's rated capacity for the drum. The mixer shall be provided with a water-measuring tank into which mixing water shall be discharged, having a visible gauge so that the amount of water for each batch may be measured separately and accurately. The mixer shall be provided with an approved batch-timing device which will automatically lock the batch-discharging device during the full mixing time and release it at the end of the mixing period.

Hand Mixing.—When hand mixing is authorised by the Engineer, it shall be carried out on a water-tight platform. The cement and fine aggregate shall first be mixed dry until the whole is of a uniform colour. The water and coarse aggregate shall then be added and the entire mass turned at least three times, or until a homogeneous mixture of the required consistency is obtained.

Retempering.—The retempering of concrete or mortar which has partially hardened, that is, remixing, with or without additional cement, aggregate or water, will not be permitted.

Central Mixing.—The use of central mixing plants and the transportation of mixed concrete is permitted provided there is no segregation of the mixed concrete when it is delivered at the point where it is to be deposited. The period between mixing and placing shall not exceed 30 minutes, and this period may be reduced at the discretion of the Engineer. The concrete must be of workable consistency when placed in position.

Cleaning.—Before beginning a run of concrete, hardened concrete and foreign materials shall be removed from the inner surface of the mixing and conveying equipment.

Retempered Concrete.—The term " retempered concrete "

in a strict sense is generally understood to mean concrete which has stood for some time after mixing and which is remixed with the addition of water before placing. The term is sometimes applied to concrete which has been allowed to stand for some time before placing, even though no additional water is added.

Most specifications prohibit the use of concrete which has been mixed more than 30 minutes, in the belief that its quality is questionable.

It should be noted, however, that retempering has been found advantageous in the elimination of laitance. The process [113] consists in mixing the concrete and storing for several hours, during which time the initial set takes place. The concrete is then returned to the mixer and re-mixed without the addition of water. It is claimed that concrete retempered within two or three hours gains slightly in strength, hardens much more rapidly, will show no shrinkage after being placed in air, or swell when poured under water, and will not lose the fines of the cement through wash to any appreciable extent. Some engineers extend the time of retempering to as much as five hours. On work of any magnitude, retempering is of somewhat doubtful value, as the time lost in storing and remixing is an important factor. The cost of furnishing the necessary hopper, cars and tracks for three hours' storage, or the construction of bins, chutes, and an elevator, or any other storage device, would necessarily be reflected in the unit cost per cubic yard to such an extent as to make the plan on many jobs unacceptable.

The following paragraph from the *1924 Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete* is an example :

> " 34. The retempering of concrete or mortar which has partially hardened, that is, remixing with or without additional cement, aggregate, or water, will not be permitted."

Some engineers recently have advocated the introduction of another " time factor " in the fabrication of concrete—premixing of the cement and water for extended periods prior to mixing with the aggregate. This premixing, or so-called " prehydration," is claimed to give increased

strength and other desirable properties, and under certain conditions facilitates the placing of the concrete.

Although engineers have had these and related questions before them for many years, only a few test data are available. Tests [114] have been carried out, however, for the purpose of determining the effect on the workability and the strength of the resulting concrete of (1) retempering with and without the addition of water, and (2) of premixing the cement and water for extended periods prior to mixing with the aggregate. The investigation included a study of the effect of the following factors or treatments on the strength and workability of concrete of a wide range of water-cement ratios after standing for periods up to six hours in air-tight cans or in pans exposed to the air of the laboratory before use :

(1) Remixing without the addition of water.

(2) Remixing with the addition of water to restore the concrete to its original condition of workability as measured by the flow test.

(3) Type of aggregate.

(4) Addition of aggregates to cement pastes which had stood for periods up to six hours.

(5) Dry and soaked aggregates.

(6) Admixtures of hydrated lime or "celite."

(7) Premixing cement and water for periods up to 30 minutes before adding aggregate, and mixing for additional periods of half a minute to ten minutes.

The principal conclusions from the tests (which were made with a blended Portland cement of normal chemical composition and physical characteristics) were as follows :—

(1) The most striking result was the small loss in compressive strength due to standing for periods up to six hours (protected from evaporation) in concrete remixed without the addition of water. When the mixtures remained plastic and workable the loss was practically nil. After the concrete ceased to be plastic the strength fell off rapidly. There was always a reduction in flow with an increase in standing period.

(2) In concrete remixed with the addition of water to restore original flow after standing for periods up to six

hours (protected from evaporation), the strength was reduced in accordance with the increase in the water-cement ratio resulting from the added water.

(3) When standing unprotected, so that water was lost through evaporation, an increase in strength resulted, due to the lowered water-cement ratio.

(4) Wetting the aggregates 16 hours in advance of mixing the concrete gave about the same strength of concrete as was obtained with dry aggregates using the same total quantity of mixing water. The workability at all standing periods was materially increased by the use of wetted aggregate.

(5) Premixing the cement and water for one minute and allowing the paste to stand for periods up to six hours before adding the aggregates resulted in a gradual reduction in the compressive strength as the standing period increased, which reduction at the six-hour period amounted to about 20 per cent. of the strength of the 0-hour period. Premixing had little effect, if any, on the workability.

(6) Increasing the time of mixing from ½ minute to 10 minutes resulted in an increase in compressive strength both for concrete mixed in the usual manner and for concrete made by premixing the cement and water before adding the aggregate. The percentage increase ranged from 10 per cent. to 25 per cent. of the strength of concrete mixed for half a minute.

(7) Tests on a 1 : 4½ concrete mixture containing 15 per cent. and 25 per cent. of hydrated lime or "celite" respectively by volume of cement, when remixed with and without the addition of water after standing for various periods, showed results similar to those obtained with concrete of the same mix without admixture. The concrete containing admixtures showed slightly higher compressive strengths than the plain concrete, but less flow after each standing period, and required the addition of more water to restore the original flow. However, the plain concrete showed higher strength than that containing admixtures when comparisons were made on the basis of equal flow and mix.

In spite of the foregoing results, and of many others

which could be quoted, the writer feels that the "retempering" of mortar and concrete is a process which cannot be recommended at present.

PLACING.

The placing of concrete is an extremely important operation, although it is often left to the unskilled workman. It is of little use having a well-designed mix if precautions are not taken to ensure that no segregation takes place and that the correct water-cement ratio exists when the material is in its final position. It is not the intention here to discuss methods of handling and transporting concrete, but it is clear that those methods which will help to place the concrete with the minimum expenditure of both time and money, and without segregation, are the ones which should receive special consideration. The question of placing concrete will be better understood after the following notes on consistency, workability and laitance have been read.

Concreting Under Water.—To obtain good concrete, when it must be placed under water, it is necessary to get the concrete in place without giving the water a chance to separate the aggregates and cement.

The simplest and probably the best method is to use a sheet iron cylindrical chute, open at both ends, with a hopper at the top. The cylindrical portion should be large enough to hold an entire batch of concrete and long enough to extend from just above the water level to the bottom of the excavation to be concreted. The chute is placed in the water and filled with concrete. It is then raised slowly just far enough to allow part of the concrete to escape through the open bottom and spread into place. The lower end of the pipe should never be emptied of concrete. This will prevent the entrance of water from the bottom.

When only a small amount of concrete is to be placed, it can be shovelled into a length of small pipe used in much the same manner as described above. This is simply and easily done. First put the pipe into position and fill it

with concrete to expel the water. Then gradually lift it a little each time you put in a batch.

All concrete placed under water should be mixed as dry as possible to reduce the danger of separation of the materials.

Concrete under water has a greater tendency to form scum or laitance than concrete above water. For this reason a mass of concrete under water should be poured in one operation, though it may require day and night work. Otherwise there will be laitance seams which will greatly reduce the strength. Walls that are partially under water should be brought above the water level before the concreting is stopped.

CONSISTENCY.

Building Research Station Summary.

Perhaps the most notable work on the consistency of cement, aggregates, etc., was that carried out by the *Building Research Station*, and the following conclusions are taken from *Technical Paper No. 5.*[115]

Consistency (or Consistence) is a property which depends mainly on the following factors :—

(1) Water content, *i.e.*, percentage of water used in mixing.

(2) Sizes of the solid particles, including the fineness of grinding of the cement.

(3) The nature of the solids, the shape of the particles, their absorptivity and solubility, and the amount of chemical action and the state of the resulting products.

(4) Temperature of the mixing water and of the resulting paste.

(5) Aeration of the cement.

(6) Amount of working or mechanical mixing.

It is preferably measured :—

(i) By the flow table method for neat cement pastes and mortars.

(ii) By the slump method or the flow table method for concrete.

No one specified consistency will give the best results under all conditions.

Under laboratory conditions that consistency which produces a mixture of the maximum density gives maximum strength and minimum permeability. This is the consistency that it is most desirable to use when possible. In practice this consistency is not always convenient; it is usually a fairly stiff mixture and may be difficult to use except for mass work. For reinforced concrete work, where the concrete has to be worked to fill the spaces between the steel bars, and between the bars and the shuttering, a thinner consistency is desirable.

It is a controversial question whether a concrete should be tested under conditions which will give the best test results, or whether the concrete to be tested should have a consistency about equal to that which it would have in practice.

In test work most of the factors which affect consistency are either invariable, or can be made constant, *e.g.* :—

(1) The nature of the cement particles is a function of the cement being tested, and cannot be varied by the test operator.

(2) The amount of aeration can be specified.

(3) The sand may either be a standard sand, such as Leighton Buzzard, or may be that actually to be employed.

(4) The time of mixing and temperature of mixing water may be specified.

The variable factor is the percentage amount of water, and we may specify for test purposes three alternatives, either

(i) that water content which gives minimum voids, or
(ii) that consistency which gives a stated spread on the flow table, or stated result in a slump test, or
(iii) the percentage amount of water to be used.

A comparison of a number of cements will show very different results, according to which of these alternatives is adopted, particularly on short-date tests. For long periods (2 or 3 years) the results are not vastly different.

Alternative (i) is probably the most scientific method, and gives the highest strength values for any particular materials and test conditions. It is laborious and not convenient to apply, however, except for laboratory work.

Alternative (ii) has the advantage that

(*a*) It is easy to apply.

(*b*) Practical conditions can be reproduced closely for test purposes and may be specified in practice as well as for laboratory work, or

(*c*) The amount of spread may be so chosen as to give approximately the strongest mix.

Alternative (iii) has little to recommend it. Although it is

Fig. 8.—The Slump Test.

easy to apply, the amount of water to produce a given consistency depends not only on the proportion of cement to aggregate, but also upon the nature of these materials and upon the grading of the aggregate. It is not a guide that can be adopted universally in practice, because though for any particular conditions the amount of water to produce a desired consistency may be determined and specified, this amount is not necessarily that required for other conditions.

The Slump Test.—A very simple [116] and inexpensive apparatus can now be obtained for the "slump test,"

making it possible to keep a careful control on water requirements.

To carry out a test the mould is placed on a non-absorbent surface and filled to a depth of four inches with the wet mix. This is then consolidated by puddling with the pointed end of the iron rod, 25 strokes being given. A second four inches are then filled and consolidated as before, the puddling only going to the depth of the surface of the first filling. The remainder of the mould is filled in a similar manner, and the surface levelled off. The mould is now lifted vertically and placed beside the test piece, obtained as described, which will have settled or slumped. The extent to which this settlement has taken place is measured in inches, and is spoken of as so many inches "slump." Fig. 8 illustrates the test in actual use.

From this description it will be seen that the test is not only simple, but quite a practicable one, that can be handled on the contract with the minimum of apparatus, and with a very slight expenditure of time.

Slump Values.—The following table gives suggested slumps for various types of work. It is rarely necessary to have a slump greater than 6 inches, whilst on the other hand, a slump less than 2 inches is apt to result in honeycombed concrete unless particular care is taken to ensure good consolidation. However, honeycombing is not likely to result with a 1-inch slump so long as the aggregates are well graded.

SLUMP VALUES.

Type of Work.	Slump in Inches.
Plain mass work, . .	2 to 3
Reinforced work, . .	2 to 5
Thin vertical members, .	5 to 6
Heavy sections, . . .	2 to 4
Roads and floors, . .	1 to 2

Chutes and Slumps.—One reason why [117] the slump test for concrete is not adopted more readily in some quarters is that contractors owning chuting plants think that only sloppy concretes (*i.e.*, having high slump values), can be chuted successfully. There may be some truth in this where precautions are not taken to get well-graded aggregates; but experience has shown that, with a little care, concrete having a two-inch slump can be delivered by chute without difficulty.

Specifications for a bridge recently completed at Los Angeles, required the use of concrete with a slump not exceeding two inches for footings, shafts of piers and abutments. The contractor successfully chuted to place both Class A and Class D concrete (specified as 1 : 2 : 3½ and 1 : 3 : 6 mixes, respectively), that was within these slump requirements. In fact, some of the Class D concrete so placed showed a slump as low as half-an-inch. The chute slope was 5½ inches vertical per foot horizontal. The materials were specially proportioned by the void method, so that the quantities, instead of being in the proportion allowed by specification, were actually 1 : 2·7 : 6·3 for Class D, and 1 : 1·58 : 3·92 for Class A. No admixtures were used. The rock was graded in two sizes, from one quarter inch to one inch, and from one inch to 1½ inches, respectively, these sizes being combined so as to correspond with a grading curve showing maximum density. Materials were measured by the batcher and sand inundator methods, mixed in a one-yard mixer, hoisted in a skip, and delivered by chute a maximum horizontal distance of 320 feet without any unusual difficulty in the delivery system.

Workability of Concrete.

Definition.—Good concrete is not merely a question of strength. The concrete must also be durable, weather-resisting, and water-resisting, and to obtain these qualities the concrete must have, in the correct degree, a property known as "workability." We can consider concrete as being "workable" when it may be transported from mixer

to place of deposit with maximum ease and minimum segregation, and when it may be deposited in place, and will give the required finish, with a minimum expenditure of effort.

The " workability " of concrete is difficult to define, since it is the direct result of several properties of the ingredients and of the mixing procedure, but it has been described as " that property which is inversely proportional to the effort required to mix and place the concrete in order to obtain a uniform and homogeneous finished product." " Consistency " should not be confused with " workability." " Consistency " depends upon the quantity of water used in the mix, whereas " workability " depends not only on this, but on the properties and proportions of the ingredients used.

The term " workability " [118] is used to describe the ease or difficulty which may be encountered in placing the concrete in a particular location. It involves not only the thought of consistency of the concrete, but also the conditions under which the concrete is to be placed—size and shape of the member, spacing of reinforcement rods, or other details interfering with the ready filling of the forms. A stiff, plastic mixture, with large aggregate, which is workable in a large open form, would not be workable, for example, in a thin wall of complicated reinforcing details.

Factors affecting Workability.—It is helpful to a correct understanding of the problem if we adopt Ahlers' suggestion and consider the mixing of concrete as being effected in three essential parts :—First, combining the cement and water (for a definite strength) to make the binder ; secondly, combining the coarse and fine aggregates to make the filler ; and, thirdly, combining the binder and filler in such a manner as to get the desired workability. In practice, of course, these operations occur simultaneously.

Assume that the correct water-cement ratio for a certain strength has been obtained. Then any degree of workability may be attained by using various proportions of binder to filler. The workability of the concrete will be increased by an increase in the proportion of binder, but so will the cost. A less costly method of increasing the workability is to

combine the fine and coarse aggregates more advantageously, or to use aggregates that have better grading. This method might even improve the workability with a reduction in cost.

Workability is also affected by mixing period and admixtures. A longer mixing period means a more workable concrete.

It should be appreciated that the workability required in any instance will depend upon circumstances. Concrete conveyed by chutes must flow easily, but without segregation, whereas for concrete transported by trucks the ease of flowing is not so important, as far as the transportation is concerned. In all cases, and particularly so for central mixing, segregation must be prevented. When the concrete has been deposited, the workability required will vary according to the type of work. Mass concrete will not need to be as workable as concrete which is to be worked into thin sections heavily reinforced.

It is clear, then, that the required degree of workability will depend on :—

(1) Mode of transport.

(2) Type of work.

(3) Importance of workability in relation to other factors, such as economy of mix.

This last point should not be overlooked, as workability will not be the only factor to consider and it may even be advisable to sacrifice a little workability to obtain some other property.

Water Content.—The variation of workability which may be obtained by varying the amount of water used is limited, except for a very rich mix. The common method of trying to get a more workable concrete is to add water without altering the proportions of the other ingredients. This is a most reprehensible practice, and should never be allowed. For lean mixes the gain in workability is only slight, and though the richer the mix the greater the variation in workability obtained, the gain will usually be more than offset by attendant disadvantages. For a given mixture,

the workability increases in approximately direct proportion to the water-cement ratio.

Admixtures.—Since the importance of workability, and its control, have been realised, there have appeared on the market numerous admixtures which are advertised to improve the workability without any ill effects. There seems little doubt that many of these are advantageous under certain conditions, but they should not be used indiscriminately.

Workability is promoted by four types of admixtures :—

(1) Those that are inert in the mix and act principally as a lubricating agent. They include such types of fine aggregate as fine silica, "pumicite," some diatomaceous earths, limestone dust, kaolin, clay, and other similar materials.

(2) Such materials as hydrated lime, blast-furnace slag, natural cements, etc., which add to lubricating properties the ability to react in the mix and have some cementitious value themselves.

(3) Materials that have a water-holding, sponge-like effect, such as "diatomite" and other porous or cellular materials. Such admixtures help to fill voids and act as an oil in the mix, permitting a better flow.

(4) Those materials that form a "gel" or colloid in the mix. Their use has been found to—

(*a*) Prevent segregation of aggregate.
(*b*) Help the "flowability" of the concrete.
(*c*) Produce more uniform and better-appearing concrete.
(*d*) Increase the average strength of the concrete.
(*e*) Increase the yield under favourable conditions.

Influence of Aggregates.—Goldbeck has suggested that if by "workability" we mean "mobility,"[119] and ease with which the concrete may be worked into position in the forms, with no surface pockets and no large internal air voids, or if we mean the ease with which the surface finish may be given to a structure such as a concrete road, then it would seem that we are dealing in a large degree, although not wholly, with a question of internal friction within the concrete, and those factors which make for low internal

friction are those which will make for ease in handling. The following characteristics of both fine and coarse aggregates must be considered in their effect on the internal friction within a concrete mass :—

(1) Shape of particles.

(2) Smoothness of surface or surface characteristics of the particles.

(3) Mechanical grading of the particles from the coarsest to the finest.

The following notes on these characteristics are taken from Goldbeck's Paper.

Shape of Particles.—As far as shape of coarse aggregate is concerned, the matter may be summed up by stating that angular fragments, for like volumetric concrete proportions, produce harsher-working concrete than rounded fragments, due, in part, to the interlocking of the coarse aggregate brought about by angularity, but, in part also, to the fact that angular particles for like gradings have higher voids than rounded fragments. This being the case, if the proportions are stated in an arbitrary manner, and the same proportions by volume are used with both angular and rounded material, there will be the same mortar content in both cases, so that the rounded fragments will be more widely separated than the angular fragments and will be better lubricated by the mortar. Hence, the mass is more mobile. Increased workability, however, may often be obtained simply by the addition of extra sand to the mix, without any sacrifice in strength, and even with an increase in strength.

Surface Characteristics.—Coarse aggregates have three general kinds of surface characteristics—(*a*) extremely smooth, as in most water-worn gravel and in certain types of flint rock, (*b*) rough, as in most crushed stone, and (*c*) extremely rough and pitted, as in blast-furnace slag. These surface characteristics probably have two effects from the standpoint of workability. In the first place, roughness of surface produces surface voids in excess of the voids which would exist were the surfaces smooth. Hence, it should be expected that less workability will result with the rough-surface aggregates, due to their increased voids

and the lesser quantity of mortar available for promoting workability. Secondly, roughness of surface probably makes for high internal friction in the concrete mass, and therefore decreased workability. There do not seem to be any specific tests covering the effect of surface characteristics on workability, but practice seems to point to the general truth that the rougher the aggregate, the less workable is the concrete, when like volumetric proportions are used.

Grading.—The following facts are indicated with regard to the gradation of the aggregates :

(1) The stiffer the mix the smaller should be the aggregates for equal workability.

(2) The higher the strength, the coarser may be the aggregate having a given maximum size. This is possible undoubtedly because of the use of more cement containing fine particles which lubricate the mass.

(3) It is possible to obtain a sufficient degree of workability irrespective of the maximum size and irrespective of the aggregate characteristics by changing the concrete proportions.

It is apparent that since a number of gradations may result in the same fineness modulus, and, further, since the gradation affects the voids in the coarse aggregate, it is quite possible to have different degrees of workability in concrete in which the coarse aggregate has the same fineness modulus.

It seems to be the case that the smaller the maximum size of coarse aggregate, the greater is the workability; and also, the more uniformly graded the coarse aggregate from maximum to minimum size, the more workable is the mix. The minimum size, for commercial reasons, is generally $\frac{1}{4}$ inch, and sand is rather universally allowed to extend up to $\frac{1}{4}$ inch in diameter. It is undesirable that the coarse aggregate have too high a proportion of particles between $\frac{1}{4}$ inch and $\frac{1}{8}$ inch in size, especially when the sand is coarse, for a "grainy" concrete will result, which will not work smoothly. A straight-line grading for coarse aggregate gives good workability, economically. Perhaps this grading may be improved slightly, however, by decreasing the

percentage of medium size particles and increasing the percentage of smaller sizes slightly. It is as well to limit the percentage passing the ¼-inch screen to 10 per cent., and preferably 5 per cent. to avoid "grainy" concrete, and there should be approximately 50 per cent. retained on the screen midway between ¼ inch and maximum size.

In general, the finer the fine aggregate, the greater will be the workability. This does not mean that the use of a fine sand is desirable, for considerations such as strength and economy require the use of as coarse a fine aggregate as will make workable concrete. A sand may produce harsh-working concrete if it has too high a percentage of particles above the No. 8 sieve, especially if there is a large percentage of small particles in the coarse aggregate. It is almost impossible to set down any hard and fast rule for limitations in the gradation of sand from the standpoint of workability. The fine and coarse aggregate combination must be considered together.

Limestone.—In one instance, substitution of limestone screenings [120] for a portion of the sand and gravel aggregate improved the workability of the mix, and permitted the removal of blocks from the moulding machine without the occurrence of the breakages so frequently encountered with sand and gravel mixes.

Prehydration.—Ahlers reports [121] that an increase in workability and strength is obtained by prehydration, or a thorough mixing of the water and cement prior to being introduced into the mixer. In some tests conducted in connection with actual field operations it was very clearly demonstrated that prehydration is most desirable, both by observation of the workability and the appearance of the concrete, and also by actual test results on test cylinders.

It should be mentioned that other investigators do not agree with this view, and it is probable that further research will be carried out to settle the point.

Measurement of Workability.—It can safely be said that no really suitable method has yet been devised for determining which of two mortars, or concretes, is better in this respect.

Working on the conclusion that the most obvious

difference between concretes of different workability was the tendency of the harsher mixes to allow their solid constituents to settle and pack at the bottom of the mass, J. C. Pearson and F. A. Hitchcock devised a simple penetration test [122] which was described before the *American Society for Testing Materials*.[123] Since then several other tests have been tried.

A three-rod penetration apparatus [124] has been developed, during the study of the plastic properties of neat cement pastes, which can be adapted to measure the workability of concrete. This apparatus confirmed the earlier findings of J. C. Pearson and F. A. Hitchcock that the workability of a concrete mixture is about equally improved by the addition of :—

9 lbs. hydrated lime,	per 94-lb. bag of cement.
6 lbs. kaolin,	
3 lbs. " celite,"	
25 lbs. additional cement	

It is interesting to note that the foregoing proportion of hydrated lime is approximately 10 per cent. by weight of the cement, which is an amount often recommended in this country.

LAITANCE.

The increasing attention which is being paid to the prevention of the formation of laitance, and to its removal, is one of the most important developments in concrete construction taking place at the present time. The immediate result is not spectacular, and at the time the work is done there is little evidence of what is really being accomplished ; but there is no doubt that the elimination of laitance from our work will lead us nearer to the realisation of the slogan " Concrete for Permanence " than anything else.

Definition.—Anyone who has carried out concrete construction to any appreciable extent is familiar with laitance, though he may not know it by that name. " Laitance " is

a word of French origin, used to denote the light-coloured powdery substance which is held in suspension when concrete is placed in water, or the accumulation of the finer particles of cement (and possibly sand) brought to the top of a too sloppy concrete mass poured in the dry. The formation of laitance is usually regarded as inevitable, but this is not so, unless dealing with concrete poured under water. Any tendency to form laitance should be counteracted, and if, by a set of unfortunate circumstances, laitance be allowed to form, it should be removed.

Composition and Nature.—To anyone unfamiliar with laitance, the following description, given by N. C. Johnson,[125] should prove adequate—Laitance is a " light semi-solid, chalky when dry, slippery when wet, non-adherent to concrete above and below it."

Twenty years ago, Taylor and Thompson [126] gave the following composition for a sample of laitance, pointing out that it is very similar to a normal Portland cement :—

	Per cent.
Silica (SiO_2),	16·00
Alumina and Iron (Al_2O_3, Fe_2O_3),	8·66
Lime (CaO),	47·40
Magnesia (MgO),	2·40
Ignition loss,	23·60

If calculated to a water and carbonic acid-free basis the analysis becomes :

	Per cent.
Silica (SiO_2),	20·94
Alumina and Iron (Al_2O_3, Fe_2O_3),	11·30
Lime (CaO),	62·04
Magnesia (MgO),	3·14

More recently, R. M. Miller [127] investigated the problem in connection with the pouring of 3,900 cubic yards of the " seal " concrete under water in steel caissons. From time to time, as the work progressed, chemical analyses were made of the laitance, samples being taken from the top and bottom of the deposit. The dried and hardened laitance was also

subjected to chemical analysis. In no case was any marked difference to be found between the chemical constituents and those of the cement used on the work. By reference to the following analyses of laitance, "Atlas" cement before using, and other Portland cements, it will be seen that the chemical constituents vary no more from those of "Atlas" cement than those of one standard brand of cement vary from those of another :—

Chemical Constituents of Laitance.			
	Laitance.	"Atlas" Cement used on the Work.	Standard Portland Cements—Handbook reference.
Moisture,	7·55	...	...
Silica (SiO_2),	22·49	21·31	19·06
Iron (Fe_2O_3) & Alumina (Al_2O_3),	7·56	6·84	9·76
Calcium oxide (CaO),	62·40	62·80	61·23
Magnesium oxide (MgO),	Trace.	2·64	2·83
Sulphuric acid (SO_3),	Trace.	1·34	1·34

The laitance was found to be of a chalky colour, hardening slowly, specific gravity 0·69, or of sufficient buoyancy to float until water-soaked. After two years samples of the laitance were still so soft that they could easily be crushed between the fingers. The substance appeared to be a mechanical mixture of the finest particles of cement with a little fine sand and silt from the bottom. When the laitance was put through a No. 200 sieve and remixed with water, a whitish mortar was formed, smelling strongly of lime.

In 1909, Edward Godfrey found by experiment that if the fines, or dust cement, lodged upon the rafters of the cement mill, were mixed in varying proportions with sand, giving from 1 : 10 mortar to neat, between the two extremes a balanced mixture was obtained. This balanced mixture was found to be 1 : 2 mortar, which showed a tensile strength of 855 lbs. per square inch for 28-day tests, compared with 165 lbs. per square inch for neat mortar, or laitance, and

134 lbs. per square inch for 1 : 10 mortar. Commenting on this peculiarity, Miller pointed out that the same thing was noticed on examining buckets of laitance that had been removed from the foundations and allowed to dry-out for several months. Small amounts of sand here and there were found in the mass of the laitance. Whenever sand was encountered, the laitance and sand zones had set into hard masses, between which masses was to be found pure laitance that crumbled readily between the fingers. In other words, the sand and the fines had formed more or less balanced mixtures.

Precautions for Concrete Under Water.—Miller [128] suggested that laitance can be kept to a minimum by the following precautions :—

(1) Use a clean aggregate.

(2) Make the bottom as free of mud as possible.

(3) Use fresh water in the mix, free from dirt, earth or sewage.

(4) Cut off all high piles that have been driven to refusal. Keep the penetration of the foundation piles into the concrete to a minimum for stability.

(5) Use mix of a relative consistency from 1 : 10 to 1 : 15, and use the slump test to keep the consistency uniform.

(6) Leave the bottom-drop bucket open at the top, but with bottom doors that open freely downward when tripped. Fill the bucket completely with concrete before being slowly lowered. When discharged the bucket should be returned slowly until clear of the concrete. An automatic trip should be installed on the bottom of the bucket so arranged that the bottom drops cannot be released until the trip has touched pile heads or concrete. If metal top doors are to be used they should preferably rest upon the charge of concrete when the bucket is full and open downward and follow the concrete as it is emptied. If the usual top doors resting upon the rim of the bucket are to be used it should be so arranged that they can be opened slowly upward before the charge is emptied.

(7) If the arrangement of the foundation piles and the shape and dimensions of the foundation caisson are such

that the tremie can be used to advantage, it is preferable to the bottom-drop bucket, in Miller's opinion, provided its nose is kept below the surface of the concrete already placed and the pipe is continually full of concrete. Every charge lost means additional laitance.

In passing it should be added that retempering of concrete has also been found of advantage in the elimination of laitance.

Construction Joints.—The foregoing remarks apply to concrete placed under water, and it is clear that laitance is caused essentially by an excess of water. We experience the same trouble with concrete placed in the dry; that is, a layer of laitance forms whenever the water present in the mix is excessive. Often this layer of fine material is ignored during construction, and it is only at some later period that the presence of faulty joints becomes noticeable. Almost any outside monolithic wall will show "day's-work" planes, first perhaps by a kind of efflorescence, then by stains, later by surface crumblings, and ultimately by serious local disintegrations.

Many say that the foregoing are unavoidable, and are to be expected in concrete work. The analyses shown on p. 225 indicate that laitance represents part of the cement and, therefore, that its formation is undesirable. Cement used to make laitance means so much less cement in the actual concrete, but, unfortunately, this is not the most serious trouble.

Formation of Laitance.—Excess water in the mix is responsible, among other things, for segregation and the formation of laitance. The fact that a layer of fine material comes to the top of a concrete wall during construction is evidence of an over-wet mix. The best thing to do is to have as dry a mix as it is possible to work into place, and avoid the formation of laitance by varying the "wetness" of the following mixes slightly, as required, so that the concrete last placed in position does not become too wet or too dry.

The "permanence" of concrete becomes little more than a myth if the structure is composed of alternate layers of concrete and laitance.

Bonding New and Old Concrete.—If, in spite of precautions, a layer of laitance be formed, it should be removed completely before fresh concrete is placed. Not only should the laitance layer be removed, but the concrete underneath should be well hacked to enable a good bond to be made.

The importance of getting a good key is fairly generally recognised, but in many cases an attempt has been made to get the key in the laitance itself. This, of course, is useless. It should not be overlooked that, on massive work, where large quantities of concrete are being placed each day, the layer of laitance may be several inches thick. The unnecessary expenditure involved in removing all this material should be sufficient to prevent the use of a series of over-wet mixes without the use of corrective stiff mixes.

Suggested Specification.—The seriousness of this question was fully appreciated by N. C. Johnson [129] when he suggested the following :—" After any form, or lift of forms, has been filled, spaded, and allowed an interval of settling not greater than half an hour, and while the concrete yet remains in a semi-fluid condition, the top portion of the forms shall be removed throughout the entire length of the section to such a depth as may be required by the engineer, and the materials shall be allowed to flow out of the forms and be wasted. This 'wasting' shall be carried to such a depth as will expose coarse aggregate in the mass. Concrete shall not again be deposited on the remaining concrete until the next lift of forms is ready to be filled."

Bonding.

Interruptions [130] in the placing of concrete are bound to occur in ordinary circumstances due to such factors as the limited capacity of concreting plant, periods between shifts, shortage of material and inclemency of the weather. The following general procedure is recommended under normal atmospheric conditions for the three cases given.

Case 1.—Bonding concrete to that which is not more than 4 hours old.

Case 2.—Bonding concrete to that which has been in position for more than 4 hours, but not longer than 3 days.

Case 3.—Bonding concrete to that which is more than 3 days old.

Case 1.—At the end of each successive layer the "laitance" film and the layer of porous concrete immediately below it must be removed before placing the new concrete.

Where possible it is advisable to fill the forms to a point slightly above the required height, and then strike off the poorer material that collects at the top, before the concrete commences to stiffen up. This procedure should not be delayed beyond a period of four hours—since tests have shown that if concrete has stiffened up too much, some of the aggregate below the surface layer may be loosened permanently by the process of removing the top layer, and the possibility of obtaining a good bond with new concrete become remote.

Having removed the top layer of concrete, the new concrete must be added immediately. The mix should be just sufficiently plastic that when tamped it will flow sluggishly into position. The use of too dry mixes will render the efficient bonding of successive layers of concrete very difficult and the concrete at the bottom of each layer will be porous. On the other hand, very wet mixes should be avoided, as these result in segregation of the aggregate and the formation of "laitance," and on setting and hardening the concrete will shrink excessively.

Case 2.—The "laitance" and porous layer should be removed as in Case 1. The surface of the concrete which has now partially hardened should be brushed with a steel wire brush and thoroughly washed with clean water to remove loose particles, dirt, sawdust, etc., that may have collected in the forms. The surface of the concrete should not be bush-hammered or "hacked" unless the material has become exceptionally hard. Cement mortar of similar composition to that embodied in the new concrete mix itself, *i.e.*, excluding the large aggregate, and of plastic

consistency, should now be applied to the prepared surface. A layer ½ inch in thickness will usually suffice. The new concrete should be placed immediately upon the mortar grout and well punned toward the joint.

Case 3.—When concrete has been allowed to mature for some time, the surface becomes very hard, and unless this hardened crust is removed, there is little possibility of effecting a good bond with the new concrete which is to be added. The hardened surface must be chipped away, the material then brushed with a wire brush and thoroughly rinsed with clean water to remove loose particles. A "slurry" of neat cement should then be applied. This should be of the consistency of a thick cream and may be applied with a brush. The "slurry" must be well worked into the interstices of the prepared surface. Cement mortar of similar composition to that embodied in the new concrete mix itself, and of plastic consistency, should now be applied, and this should be followed immediately by the new concrete, which should be well punned towards the joint.

A method which gave excellent results in the laboratory, but which would in practice entail a considerable amount of supervision, was to follow the neat cement "slurry" with a cement mortar composed of two parts of cement and one part of sand (proportions by weight) and again follow by a cement mortar composed of one part of cement and two parts of sand (proportions by weight), before placing the new concrete. In this manner a more even gradation of the material at the joint was obtained, which reduced differential shrinkage. Almost without exception failure of beams jointed in this manner occurred away from the joint, showing that the adhesion at the joint was ideal.

Bond Between Aluminous and Portland Cements.—The results of very few tests on the bond between aluminous cement concrete and Portland cement concrete have been made available, but the following tests, which were carried out in America,[131] indicate that an adequate bond is developed. Six half briquettes of Portland cement mortar were replaced in the moulds and the rest of the space filled with aluminate cement mortar. The new briquettes formed in this manner were broken at the end of 24 hours and

showed bond strengths of 280, 125, 325, 240, 95 and 190 lbs. per square inch, or an average of 209 lbs. per square inch. In one case about half the fracture was through the old Portland mortar instead of being all at the bond.

Winter Work.

General.—There is no reason why in Great Britain more concrete work should not be carried out in the winter months than is generally the case. Concrete placed during the cooler months of the year is most successful, chiefly because the moisture is only released slowly by the concrete.

Concreting may continue while the temperature is above 35° F. without special precautions being taken, unless there is a tendency for the temperature to fall still lower. If the latter is the case, the proportion of cement should be increased for the concrete mixed during the last hour's work. It should be understood clearly, however, that the setting and hardening of concrete are considerably retarded at temperatures below 40° F.

If the concrete is cooled to a temperature below freezing point before the cement has set, the water in the concrete will freeze and there is risk of damage by disintegration of the surface. When frosts are likely to occur, the concrete should be protected from contact with cold air as soon as possible after laying.

Concrete possesses a measure of self-protection against frost, because heat is developed during the setting of the cement, and, if this heat can be retained by a suitable covering, frost is hardly likely to be damaging. Considerable discretion must be used in the removal of shuttering from walls, beams and floors, because of the slow rate at which concrete hardens below temperatures of 40° F.

Roads.—The best method of protecting roads is by means of tarpaulins above the concrete, with an air space of a few inches between the tarpaulin and the surface of the slab. The edges of the tarpaulin should be on the concrete itself, kept down by weights, so that there is no circulation of air beneath. Alternatively, the concrete may be protected

from the cold air or winds by hessian canvas laid directly on the surface—the fact that the hessian may mark the surface is of no consequence. As soon as the cement is set it may be protected by a layer of sand, shavings or sawdust.

Structural Work.—External wall construction may be continued at a temperature of 35° F., but the shuttering should be covered with old sacks as soon as the concrete is placed, good keys being left as usual for the next lift. When wooden shuttering is used, little protection, if any, is needed for the sides, and it is necessary only to cover the top of the wall with two or three layers of old sacks.

The proportion of cement must be increased if it is desired to remove the shuttering at the same periods as are allowed for a temperature of 60° F.

Floors need protection, especially near openings; the central portions will be affected only by a very severe frost.

Job Rules.

The following rules, formulated by A. R. Lord [132] in connection with the construction of the Wacker Drive, Chicago, are worthy of reproduction, since anyone working to them would make certain of obtaining good concrete.

"(1) All the concrete in an outdoor structure should be strong, dense and impervious, while every part of every reinforcing bar should be protected by at least 1 inch and in some cases by 1½ to 2 inches of good concrete or mortar.

"(2) While good concrete may be made from a wide variety of materials, a careful study of the concrete materials available for this work will be necessary to get the best results without increase in cost.

"(3) The source of each material must be such as to ensure an adequate supply of material of constant qualities, so that a mix, once determined, can be continued through each stage of the work. Unless the contents of each batch can be successfully standardised and maintained uniform, it will not be possible to keep to that degree of stiffness which is most desirable.

"(4) Sufficient time should be reserved before field operations to make preliminary tests of concrete from available materials. These tests need not be elaborate or expensive, but they should be thoroughly well made.

"(5) While the water-cement ratio is of primary importance, as indicating strength of workable mixtures, this relation is not the same for all cements and all aggregates nor for all gradations of aggregate from the same source. It must be determined in advance for the particular materials to be used.

"(6) For outdoor concrete, workability must be limited to a very narrow range, between that stiffness where concrete begins to crumble and that wetness where concrete begins to segregate. This range, measured as slump, will vary greatly with different aggregates, and should be determined in the preliminary tests.

"(7) The equipment is hard to change when once installed, and the best kinds should be selected. Some mixers refuse to give up a batch of very desirable stiffness. Some conveying devices absolutely ensure segregation, except under extraordinary circumstances. Measuring devices must be such as to ensure repetitions for all materials batched.

"(8) An adequate mixing time should be maintained rigidly. As long mixing requirements naturally involve large-size mixers, and as large-size mixers in turn require longer mixing time, the usual specification of one minute is too small rather than too large.

"(9) The workmen largely influence the concrete. Men who by temperament or habits are opposed to the manufacture of concrete in accordance with an exact, unvarying recipe, must be eliminated from key positions.

"(10) Having spent time and money in producing a uniform concrete at the discharge of the mixer, segregation during transportation and placing must be prevented.

"(11) Freshly placed concrete must be protected from drying-out. Curing conditions involving adequate heat and moisture supplied simultaneously and continuously for at least seven days must be ensured, if strong and impermeable concrete is to be obtained.

" (12) Inspection must be adequate to ensure that :

(a) Every batch that goes into the forms is properly proportioned and mixed.

(b) All spaces within the forms are filled solid full of concrete.

(c) Every bar is away from the surface, as shown on plans.

" (13) Inspectors should be inspected and assisted.

" (14) Great consideration is desirable before anything is added to the indispensable contents of concrete."

CHAPTER XII.

CURING.

The Importance of Curing.—The importance of curing concrete has been stressed so much during the past few years that it seems incredible that there is anyone in the concrete industry who does not know the whole story. In spite of this, there is relatively very little effort made on the part of engineers and contractors to ensure that concrete may receive proper curing treatment, with the exception of the case of roads and in some cases floors.

For durable concrete, thorough curing is absolutely essential, and the usual methods are to cover the surface with wet sand, to keep it under water, or to spray it with water at regular intervals. To eliminate these somewhat cumbersome methods, various surface coatings are now being made for application to the exposed surface of freshly finished concrete.

Concrete hardens as a result of the chemical reaction between the cement and the water, and this process continues so long as conditions are favourable, *i.e.*, suitable temperature and the presence of moisture. Nearly all concrete, however, contains more water than is required for this chemical hydration, and the problem of curing may be regarded as the problem of preventing the too-rapid evaporation of this water.

Temperatures below 50° F. are unfavourable for satisfactory curing at early ages, and below 40° F. the curing is greatly retarded. Fig. 9, based on data taken from *Bulletin 81, Engineering Experiment Station, University of Illinois*, shows the effect of temperature on the strength of concrete which has been cured in a moist atmosphere and tested whilst in a wet condition.

Laboratory Results.—A laboratory investigation was undertaken to obtain information on the relative

effectiveness of many of the methods advocated for curing concrete roads, and results were reported in a Paper by H. F. Gonnerman.[133] The tests included 17

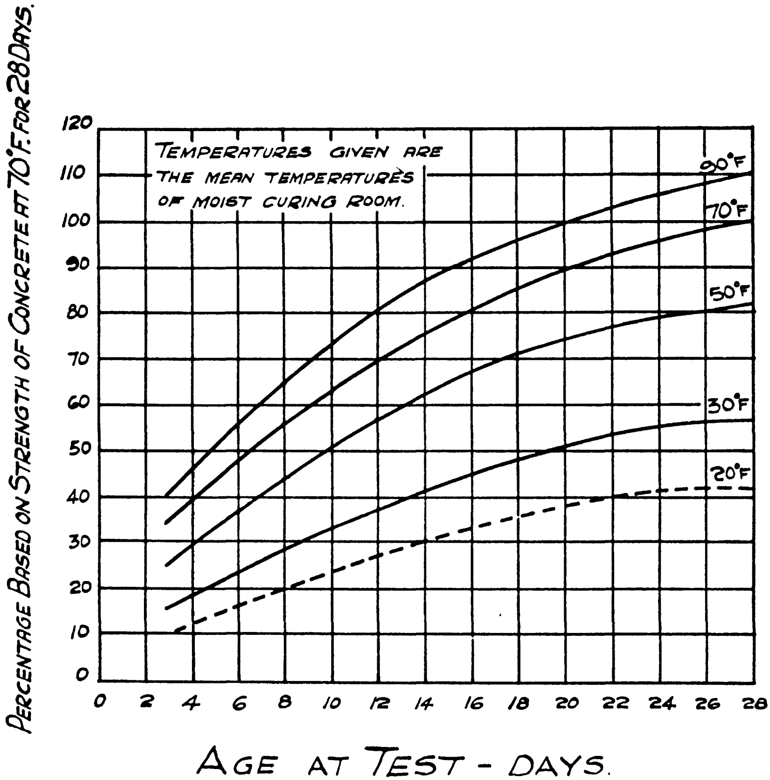

Fig. 9.—Curing and Temperature.

different methods grouped into four general classes as follows :—

1. Water curing.
2. Surface coatings.
3. Calcium chloride admixture.
4. Calcium chloride surface covering.

It is not considered necessary to give the results in detail, but the following conclusions are of interest.

Cylinders cured in Sisalkraft bags, or by means of "*Tarvia*," "*McEverlast Paint*," "*Curcrete*," linseed oil or paraffin, had approximately the same strengths at the various ages as cylinders cured in the moist room for 13 days. Compressive strengths for these methods ranged from 75 to 85 per cent. at 3 months and from 58 to 76 per cent. at 1 year of the strength of cylinders cured continuously in water.

The lowest compressive and flexural strengths were obtained on air-cured specimens with and without admixture of calcium chloride, and with specimens coated with sodium silicate. For these methods the strengths at 1 year were about half those of specimens cured continuously in water, and about 70 per cent. of those of specimens cured for 13 days in the moist room. From these results it would appear that the coating of sodium silicate was of little or no value as a means of curing the concrete ; also that the admixture of calcium chloride, while increasing the early strength, was not a satisfactory substitute for a few days of moist curing.

In the discussion to Gonnerman's paper, B. Moreell stated that where there is a large daily variation of temperature, there is considerable absorption of heat by black coatings, and the concrete is called upon to resist temperature variations at the very period in its life when it is not able to do so. In other words, we lose the insulating blanket that is obtained by the use of earth or straw curing.

In a hot climate, the effect of the insulating blanket obtained by the use of wet earth or straw is something which should not be neglected.

In the same discussion R. F. Remler pointed out that the value of silicate of soda curing depends upon the setting of a gelatinous film, and the greater the drying elements, the more rapidly this film is produced. This is the time when curing is most needed and when silicate of soda is most effective. However, these are not the conditions found in the laboratory tests. The average laboratory tests have given results with silicate of soda far below actual field tests, or tests on cores from actual construction work.

It is difficult to obtain a satisfactory film of silicate of soda on a vertical surface, especially an oil-coated surface produced by oiled moulds.

The wear tests reported by Gonnerman show silicate of soda inferior to the bituminous methods of curing. This is not in accord with field tests made by the *U.S. Bureau of Public Roads* and reported in the Feb. 1930 issue of "*Public Roads*."

In answering the discussion, Gonnerman stated that one should be able to evaluate with considerable precision the relative merits of different methods of curing concrete by means of laboratory tests. Results of field and laboratory tests might differ in degree, but the order of merit, at least so far as strength, absorption and resistance to wear were concerned, might be expected to remain the same if the tests were conducted on a comparable basis. He had used silicate of soda in four different investigations, some of which were carried out in the field where exposure to sun and wind were involved [134] and where there was every opportunity for the action described by Remler to take place. In all of these investigations the results obtained in the field confirmed those obtained in the laboratory in showing that this method of curing was little better, if any, than no curing.

Surface Coatings.—For reference purposes the following descriptions are given of the surface coatings used in the foregoing investigation and their method of application.

"*McEverlast Paving Special*," used in Hunt Process, was composed chiefly of Trinidad Lake asphalt and "Gilsonite" blended at a high temperature. One coat of the paint was sprayed on to the fresh concrete by compressed air immediately after finishing, at the rate of about one gallon for each 20 square yards of surface. The paint did not penetrate the concrete, but upon drying formed a thin coating over the surface which could be lifted with the fingers after 2 or 3 hours, while the concrete was still soft. After 24 hours the paint had thoroughly dried and hardened, forming a coating which adhered tightly to the hardened concrete.

"*Tarvia K.P.*"—This is a cold patch tar cut back with

light oil, applied with brush when the concrete was removed from the forms after 24 hours. The concrete was protected with wet burlap until the "Tarvia" was applied. A single coat was applied cold, one gallon covering approximately 20 square yards of surface. The "Tarvia" did not dry as rapidly as "McEverlast paint," but after 48 hours had dried sufficiently so that no stickiness was observable, although it was slightly soft.

"*Curcrete.*"—This is an asphalt emulsion containing about 50 per cent. water. The emulsion was sprayed on to the fresh concrete immediately after placing, at the rate of about one gallon for each 10 square yards of surface. Some difficulty was experienced in applying "Curcrete" to vertical surfaces of specimens, as it did not adhere readily to the concrete, and two or three coats had to be applied before the concrete was sufficiently protected. "Curcrete" did not dry rapidly, and at 3 months some stickiness was still observable.

Paraffin.—One coat of paraffin was applied hot with a brush, forming a covering approximately $\frac{1}{16}$ inch thick. Two sets of wear blocks were cured with paraffin coating, one set being tested with the coating on, and the other with coating removed. No appreciable difference in wear was found for these two sets of specimens.

Sodium Silicate.—"Grasselli R.B. Silicate of Soda," a syrupy liquid, was mixed with sufficient water to give a density of 36° to 37° Baumé; this mixture required approximately 1 part water to 4 parts silicate by volume. The concrete was protected with wet burlap until the silicate was applied after 1 day in the moulds. Sufficient material of the required density was mixed and applied to the surface of the specimens with a brush at the rate of about 1 lb. silicate per square yard of surface; three coats were required for this quantity of silicate, applied about an hour apart. The silicate gave a glossy, varnish-like surface to the concrete.

Linseed Oil.—One gallon of raw linseed oil was applied cold in three coats covering approximately 15 square yards of surface. The coatings were applied at one-hour intervals. The oil discoloured the concrete slightly, giving it a yellowish tinge.

Sisalkraft Paper Bags.—One beam, or six cylinders, was placed in a bag made from Sisalkraft paper, the top of which was folded over several times and a weight placed upon it. The specimens appeared to be damp when removed from the bags at ages up to 28 days.

Surface Covering of Calcium Chloride.—The concrete was protected with wet burlap for 24 hours after placing, when commercial flake calcium chloride, containing 75 per cent. of the anhydrous salt, was sprinkled over the top surface of the specimens in the forms. Deliquescence of the calcium chloride started immediately after placing, but was not complete for about 24 hours. The top edges of the specimens were dyked with paraffin to prevent moisture from running off. Moisture was retained on the top of the specimens for several days before soaking into the concrete or evaporating. The penetration of the calcium chloride into the concrete ranged from $\frac{1}{16}$ inch to $\frac{3}{8}$ inch.

Pavement Results.—Earth curing [135] has been used widely and it has been demonstrated many times that this method, properly carried out, is a very satisfactory one, so far as strength of the resulting concrete is concerned. There are two principal disadvantages to the method : First, the cost, arising from the large amount of material which must be handled and from the fact that the water supply must be maintained for the duration of the curing period ; and, second, the possibilities of controversy between the engineer and the contractor over compliance with the curing specifications. This difficulty, too, would tend towards increased cost.

Several other methods of curing, involving the use of other materials, have been promoted, and because of the possibilities for economy, they are receiving serious consideration wherever concrete pavements are being laid. In an effort to determine the advantages and disadvantages of these various curing treatments numbers of investigations or tests have been conducted by the various State highway departments and other agencies. The findings of the different investigators have not been wholly concordant, and engineers, in general, have not been entirely satisfied with the information available.

The *Bureau of Public Roads* recently has completed a study of the data obtained from curing experiments at the Arlington Experiment Farm, Virginia. In summarising what seem to be the most important indications of the data obtained from this investigation, no attempt is made to establish the relative merits of the various curing materials used. It is believed that the evidence obtained is neither sufficiently comprehensive nor sufficiently conclusive for such a purpose. However, there are indications which seem quite clear, and these are presented below :—

1. Careful attention to curing improves the quality of the concrete both from the standpoint of strength and that of surface appearance.

2. Any curing method, to be effective, must commence as soon as the concrete surface is finished.

3. All things considered, the wet burlap-wet earth curing method used in these tests was more effective than any of the other methods used.

4. The immediate application of wet burlap largely prevented the surface checking so prevalent in those slabs where the curing was delayed.

5. Under adverse conditions concrete may lose as much as 40 to 45 per cent. of the original mixing water during the first few weeks after placing and, more important, under these conditions as much as 75 per cent. of this loss may occur during the first 24 hours.

6. The application of a black surface to concrete slabs causes greater temperature variations and consequent volume changes to take place than would otherwise be the case, and under certain conditions this may result in an abnormal amount of transverse cracking.

7. The use of transverse joints which will allow free longitudinal movement of the slab ends is of material benefit for the control of transverse cracking.

8. The method used for curing a concrete pavement may affect the surface hardness.

9. Increasing the percentage of continuous longitudinal reinforcing steel decreases the average slab length.

Coloured Concrete.—Efflorescence is a serious matter where coloured concrete work is concerned, and efforts should be

made to eliminate the causes of the trouble. It can best be prevented by limiting the amount of water used in gauging, since the quantity of lime liberated from cement increases with the amount of water used. Also, if the surface of freshly moulded cement is treated with water, an extra amount of lime will be liberated on the surface, with a consequent liberal production of efflorescence. The face of coloured cement work should, therefore, not be moistened, but the curing should be effected by shielding the surface from the sun and wind to delay the drying of the moisture inside the material. Damp sacks placed over, but not in contact with, the surface, will answer the purpose admirably.

Hot Water Curing.—The first of a series [136] of investigations planned by the *German Reinforced Concrete Committee* for the purpose of studying the effects on the strength of concrete of the high temperatures encountered in hot-water tanks, chimneys and the like, has been carried out at the Testing Laboratory at Stuttgart. O. Graf, who reported the results, draws the following conclusions: Specimens stored continuously in water give higher tensile and compressive strengths than specimens stored for an initial period in water, then for 7 weeks in air, and finally in water. After storage in water at 90° C., commencing 7 or 56 days after moulding, the tensile and compressive strengths of the 1 : 3 mortars are at first not very different from those of the specimens stored in water at 20° C., but later there is a distinct reduction of compressive strength. On the other hand the tensile and the compressive strengths of the 1 : 6 mortars were considerably enhanced by storage in water at 90° C. When the hot water storage was commenced 7 days after moulding, the strengths of the 1 : 6 mortars were greater at the age of 3 months than those of the 1 : 3 mortars of the same age. The 1 : 6 mortars also displayed a marked increase of strength when stored in water at 90° C. 56 days after moulding. Storage in water at 50° C. commencing 7 days after moulding produced no appreciable change of compressive strength with two of the cements tested; with one cement the compressive strength was considerably higher than when the cement was stored in water at 20° C., with two cements there was

a loss of tensile strength, and with one the hot water storage was associated with an increase of tensile strength. Curing in water vapour at 50° C. gave higher tensile strengths than curing in water at the same temperature. Alternating storage in water at 90° C. and water at 20° C. with no intermediate pause for cooling produced lower strengths—especially lower tensile strengths—than did continuous storage in water at 90° C. Rapid heating to 90° C. and rapid cooling to 20° C. gave rise to strains which led to the development of cracks. The influence of the alternate storage varied for the different cements, so that, in practice, considerable importance will attach to the selection of the cement. Gradual changes of temperature over smaller ranges produced smaller losses of tensile strength. Several of the specimens stored in hot water displayed efflorescences which were found to consist in the main of calcium hydroxide and calcium carbonate in the form of aragonite.

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INDEX.

A

ABRAMS' water-cement ratio theory, 167.
Abrasion test, 86.
—— —— values, 88, 92.
Absorption of aggregates, 196.
Accelerators, 126.
Acid, Humic, 160.
—— slag, 69.
——, Tannic, 163.
Admixtures, 125.
—— and high early strength, 187.
—— — workability, 219.
Aeration and setting time, 27.
—— before soundness test, 23.
—— of cement, 26.
Aggregate, Ratio of fine to coarse, 180.
——, Requirements of, 60.
——, Standard, 15.
Aggregates and water ratio, 171, 178.
—— — workability, 219.
—— — ——, Grading, 221.
—— — ——, Shape of particles, 220.
—— — ——, Surface characteristics, 220.
—— for white cement, 52.
—— in concrete, Quantity of, 59.
Alum, 149.
Aluminium stearate, 156.
Aluminous cement, 2, 44.
—— ——, Characteristics of, 46.
—— ——, Composition of, 48.
—— ——, Fineness of, 48.
—— ——, Heat on setting of, 49.
—— ——, Instructions for use of, 47.
—— ——, Setting time of, 48.
—— ——, Soundness of, 49.
—— ——, Specification for, 48.
—— ——, Storage of, 48, 50.
—— ——, Strength of, 46, 48, 49.
—— ——, Tests for, 48.
American gallon, 168.
—— sieves, 75.
Analysis, Chemical, 72.
——, Mechanical, 72.
——, Mineralogical, 72.
—— of aggregates, 71.
—— of pozzolanas, 138.
——, Sieve, 74.
Aniline and pigment, 136.
Anti-freezing materials, 126.
Arable soil, Sand from, 160.
Artificial aggregates, 64, 66.
—— cements, 1.
—— pozzolanas, 140, 141.
" Atlas " cement, 2, 51, 225.
Attrition test, 86.
—— —— for gravel, 89.
—— —— values, 88.
Augite, 133.

B

BALLAST, 65.
——, Burnt, 68.
" Balling " of cement, 31.
Barium chromate, 134.
Basalt, 65, 66.
Basic slag, 69.
Bauxite, 2, 45.
Black pigment, 132.
Blast-furnace cement, 2, 55.
—— slag, 55, 140, 219.
Blue pigments, 133.
——, Prussian, 133.
——, Ultramarine, 133.
Bond between aluminous and Portland cements, 230.
Bonding, 228.
—— new and old concrete, 228.
Breeze, 66.
Brick, Broken, 67.
——, Crushed, 141.
Broken brick, 67.
—— ——, Porosity of, 68.
—— concrete, 114.

Brown pigment, 134.
Bulk of sands, 82.
Bulking, 192.
Burning plant, 4.
Burns with cement, 38.
Burnt ballast, 68.
—— clay, 141.
—— umber, 134.
Bushel of cement, 30, 191.

C

CAKED cement, 35.
Calcium chloride, 150, 151, 237, 240.
—— sulphate, 67.
Carbon black, 132.
—— dioxide and cement, 27.
Carbonates, Effect of, 161.
Casein, Effect of, 152.
Caustic soda for colorimetric test, 95.
"Celite," 140, 209, 210, 223.
Cement and water ratio, 174.
Central mixing, 206, 207.
Ceramic pozzolanas, 141.
Chatelier test for soundness, 7, 23.
Chemical analysis, 72.
—— deposits, 66.
Chert, 114.
Chlorides, Effect of, 161.
Chromic oxide, 133.
Chutes and slumps, 216.
"Ciment Fondu," 45, 159.
Clay, 219.
——, Burnt, 141.
—— in aggregate, 95, 97.
——, Test for, 98.
Cleaning of mixer, 207.
Cleanness of aggregate, 95.
Clinker, 66, 141.
Coal black, 133.
——, Effect of, 66.
Coarse aggregates, American tests, 60.
—— ——, Characteristics of, 60.
—— ——, German tests, 62.
—— material in aggregate, Value of, 73.
Coefficient of wear, French, 86.
Cold plunge test, 23.
—— weather, 231.
Colloid admixtures, 219.
"Colorcrete," 53.
Colorimetric test, 95.
Colour of cement, 32.
Coloured cements, 52, 131.
—— concrete, 241.
Colouring ability of pigment, 135.
—— material, 128.
Colours and strength of concrete, 132.
Combining aggregates, 78.
—— —— by fineness modulus method, 79.
Commercial names of aggregates, 64.
Composition of aluminous cement, 48.
—— — of laitance, 224.
—— — Portland cement, 7, 13.
Consistence, 212.
Consistency, 173, 212.
—— and diatomaceous earth, 145.
Construction joints, 227.
Consumption of cement, 58.
Cost of cements, 51, 57.
—— — concrete, 44.
—— — pigment, 132.
—— — tests on aggregates, 107.
—— — white cement, 51.
Cover of steel in reinforced work, 232.
Crimson lake, 134.
Crushed bricks as pozzolanas, 141.
—— tiles as pozzolanas, 141.
Cube, Test, 179.
"Curcrete," 237, 239.
Curing, 187, 233, 235.
—— and temperature, 236.
—— experiments, 235, 241.
Cylinder, Test, 179.

D

DEBRIS in aggregate, Removal of, 98.
Definition of aggregate, 59.
—— — laitance, 223.
—— — workability, 216.
Delivery of cement, 25.
Design of mix, 170.
—— — pavement concrete, 179.
Designing concrete, 165.
Deterioration of cement in store, 37.
Deval test, 85, 86.
Diatomaceous earth, 140, 143, 219.
—— —— and consistency, 145.
—— —— and efflorescence, 145.
—— —— and segregation, 145.
—— —— and strength of concrete, 145.
Diatomite, 219.
Diorite, 65.

Dirt in aggregate, 95.
Distilled water, 158.
Dolerite, 65.
Dorry test, 86, 88.
Dual-type pozzolana, 140, 142.
Dust in aggregate, 95.
Dust-coated stone, 99.
Dyes, 128.

E

Early strength, 186.
Earth curing, 240.
Effective water ratio, 169.
Efflorescence, 241.
—— and diatomaceous earth, 145.
—— and pigment, 135.
Eisen Portland cement, 55.
"Electric" cement, 46.
Elutriator, 12.
English sieves, 75.
Equation for water ratio theory, 169.
Equipment, 233.

F

Failures due to aggregates, 63.
False set, 18.
Ferric oxide as pigment, 133.
Fertiliser factory effluent, 161.
Field test for setting and hardening, 19.
—— —— — soundness, 23.
"Fifth" ingredient, 127.
Fine grinding, 30.
Fineness modulus, 74, 76, 170.
—— of aluminous cement, 48.
—— of pigment, 134.
—— of Portland cement, 7, 9.
—— of rapid-hardening Portland cement, 40.
Fire resistance and pozzolanas, 139.
"Flash" set, 36.
Flat pieces of aggregates, 105.
Flexural strength and water ratio, 182.
Flour in cement, 12.
Flow table, 213.
Formation of laitance, 227.
Formwork and rapid-hardening Portland cement, 43.
"Foxy" cement, 33.
Free lime, 138.
French coefficient of wear, 86.
Frost and calcium chloride, 150.
—— and rapid-hardening Portland cement, 42.
—— and sodium chloride, 150.
Frosty weather, 22.
Furnace clinker, 141.
Fused cement, 46.

G

Gaize, 142, 146.
Gallon, American, 168.
——, Imperial, 168.
Gels as admixtures, 219.
Geological classification of rocks, 65.
Gillmore test for setting, 18.
Glass as aggregate, 116.
Gneiss, 65.
Grading of aggregates, 73, 77.
—— — —— for blocks, 80.
—— — sands, 82.
——, Voids and weights, 103.
Granite, 65, 66.
Gravel, 66.
Green pigment, 133.
Grinding and soundness, 23.
—— plant, Cement, 5.
Gypsum in cement, 13.
—— plaster, 51.

H

Hand mixing, 204, 207.
Hardening of cement, Field test for, 19.
—— — concrete, 235.
Hardness test, 86.
Heat during setting, 19.
—— —— —— of aluminous cement, 49.
High alumina cement, 45.
—— early strength, 186, 188.
—— —— —— and admixtures, 187.
—— —— —— and mixing, 187.
—— —— —— and water ratio, 187.
"Honeycombing," 78, 174.
"Hot" cement, 28.
—— water curing, 242.
Humic acid, Effect of, 160.
Hydrated lime as admixture, 209, 210, 219, 223.

Hydration, Water for, 190.
Hydraulic lime, 51.
—— modulus, 14.

I

Igneous rocks, 65, 66.
"Immediate immersion" test, 24.
Imperial gallon, 168.
Impurities, 158.
Infusorial earth, 140.
Inspection, 234.
Integral waterproofers, 157.
Internal friction, 219.
Inundation, 194, 195.
Inundator, 193.
Iron as admixture, 153.
—— Portland cement, 55.

J

"Jar" paper sack, 26.
Job rules, 232.
—— strength, 42.
Joints, Construction, 227.
Jute sacks, 25.

K

Kaolin, 219, 223.
Keene's cement, 67.
Kerbs, B.S. Specification for, 10, 39.
Kieselguhr, 140.

L

Laitance, 212, 223, 229.
——, Composition of, 224.
——, Formation of, 227.
——, Nature of, 224.
Lampblack as pigment, 133.
Lead sulphide in spar, 119.
"Lewis test," 89.
Light and pigment, 135.
"Lightning" cement, 45.
Lime and pigment, 135.
—— as admixture, 154.
Lime, Effect of, 67.
——, Free, 138.
—— green, 133.
——, Hydrated, 209, 210, 219, 223.
——, Hydraulic, 51.
—— in cement, Proportion of, 23.
Limestone, 65, 66.
—— and workability, 222.
—— dust, 219.
Link trass, 141.
Linseed oil and curing, 237, 239.
"Lumnite" cement, 46, 93.

M

Machine mixing, 204, 206.
Magnesia and soundness, 23.
Manganese black, 132.
—— dioxide as pigment, 132.
Manufacture of Portland cement, 3.
Mattimore test, 89.
McEverlast paint, 237, 238.
Measurement of workability, 222.
Measuring aggregates, 192.
—— cement, 191.
—— constituents, 191.
Mechanical analysis, 72.
—— sediments, 66.
Medium-setting grade of Portland cement, 22.
"Medusa" cement, 2, 51.
Metamorphic rocks, 66.
Mica, 98.
Mineralogical analysis, 72.
Minion, 116.
Mixers, 233.
Mixing, 203.
—— and high early strength, 187.
—— — strength, 203.
—— — workability, 203.
——, Central, 206, 207.
—— colour with cement, 131.
——, Hand, 204, 207.
——, Machine, 204, 206.
——, Specification for, 206.
——, Time of, 205, 207.
Modern cements, 1.
Moisture in aggregate, 106, 172, 196.
—— — fine aggregate, 192, 193.
—— — sand, 197.
—— — ——, Determination by displacement, 197, 199, 201.

Moisture in sand, Determination by drying in oven, 197, 198.
—— — ——, —— by drying with alcohol, 197, 198, 200.
—— — ——, —— by moisture meter, 197, 198.
—— — ——, —— by specific gravity, 197,199.
Moler, 140, 146.
Moorland water, 160.

N

Natural aggregates, 64.
—— cements, 1, 219.
—— pozzolanas, 140.
Nitrogen pentoxide in mixing water, 161.
Normal Portland cement, 1.

O

Occurrence of aggregates, 64.
Old specifications for cement, 7.
Organic colours, 130.
—— deposits, 66.
—— matter in aggregates, 95.
—— —— in pigments, 134.
Oxide colours, 130.
—— of iron, 132, 133, 134.

P

Packages for cement, 25.
Paper sacks, 25, 26.
Paraffin in curing, 237, 239.
Peat, Effect of, 160.
Pebbles, 65.
Pigments, 128, 130, 136.
Piles and rapid-hardening Portland cement, 43.
Placing concrete, 211.
—— —— under water, 211, 226.
Plaster, Effect of, 67.
——, Gypsum, 51.
Pore fillers, 126.
Porosity of broken brick, 68.
Porous aggregates, 106.
Portland blast-furnace cement, 2, 55.
—— cement, Normal, 1.
Pozzolanas, 126, 137.
——, Analysis of, 138.
——, Artificial, 140, 141.
——, Ceramic, 141.
——, Dual-type, 140, 142.
——, Fire resistance and, 139.
—— in use, 139.
——, Natural, 140.
——, Types of, 140.
Pozzolanic action, 138.
Prehydration, 222.
Preservatives, 126.
Properties of Portland cement, 5.
Proportioning by volume, 193.
—— — weight, 193.
Proportions, 191.
——, Determination of, 181.
——, Variations in, 194.
Protection in cold weather for roads, 231.
—— — —— —— — structures, 232.
Prussian blue as pigment, 133.
"Pumicite," 219.
Pyrites, 67.

Q

Quality of cement, 6.
—— — pigment, 131.
—— — water, 158.
Quantities, 202.
Quantity of water, 189.
—— — ——, Variation in, 196.
Quarry owners and quality of aggregates, 79.
Quartzite, 65.
Questionnaire for admixtures, 127.
Quick-setting, 16, 156.
———— cement, 56.
"Quickening-up," 22, 36.

R

Rapid-hardening, 16.
———— Portland cement, 1, 39.
Ratio of fine to coarse aggregate, 180.
Raw mill plant, 4.

Rea test, 89.
Red pigment, 133.
Retempered concrete, 207, 227.
Roads and rapid-hardening Portland cement, 43.
Rocks, Geological classification of, 65.
"Roman" cement, 56.
—— mortar, 138.
Rottenstone as admixture, 140.
Rules for cement store, 37.

S

Salt, 66, 153.
Samples of aggregate, 71.
—— — cement, 8.
Sand, 66.
—— content and water ratio, 83.
——, Sea, 116.
——, Stone, 120.
Sands, Standard, 14.
Sandstone, 65, 66.
Santorin earth, 140.
Schist, 65, 66.
Sea sand, 116.
—— water, 162.
Seasoning of slag, 69.
Sedimentary rocks, 66.
Segregation and diatomaceous earth, 145.
Setting and hardening of cement, 16, 42.
—— and temperature, 19.
——, Gillmore test for, 18.
—— of cement, Field test for, 19.
—— periods, 50.
—— time, 17.
—— —— and aeration, 27.
—— —— and electrical conductivity, 18.
—— —— and pressure, 17.
—— —— and storage, 35.
—— —— of aluminous cement, 48.
—— —— of Portland cement, 7.
——, Vicat test for, 18, 19.
Shaley gravel, 117.
Shingle, 118.
Shrinkage and calcium chloride, 151.
Sieve analysis, 74.
Sieves, American, 75.
——, English, 75.
—— for fineness modulus, 74.
Silica, 219.
Silicate of soda and curing, 237, 239.
—— — —— as admixture, 155.
Silt in aggregate, 95.
"Sirapite," 67.
"Sisalkraft," 237, 240.
"Si-stoff," 141, 147.
Slag, Blast-furnace, 55, 64, 69.
Slump, 194.
—— test, 213, 214.
—— values, 172, 215.
Slumps and chutes, 216.
Slurry, 3.
"Snowcrete" cement, 2, 51.
Soda as admixture, 156.
Sodium chloride and frost, 150.
—— hydroxide test for organic matter, 95.
—— sulphate test for soundness, 107.
Soil, Arable, Sand from, 160.
Soluble silica in pozzolanas, 138.
Soundness of aluminous cement, 49.
—— — cement, 23.
—— — —— and grinding, 23.
—— — —— — magnesia, 23.
—— — ——, Field test for, 23.
—— — Portland cement, 7.
—— test for aggregates, 107.
Spar, 64, 118.
Specific gravity of cement, 34.
—— —— — gravel, 102.
—— —— — rocks, 102.
—— —— — sand, 101.
—— —— — slag, 69.
Specification for aggregate, 121, 122.
—— — aluminous cement, 48.
—— — cement, 7, 58.
—— — coarse aggregate, 121.
—— — concrete, 171, 173, 185.
—— — fine aggregate, 121.
—— — integral waterproofer, 157.
—— — Portland cement, 7.
—— — rapid-hardening Portland cement, 40.
—— — water, 158.
—— — —— ratio, 171.
—— to avoid laitance, 228.
Spent oil shale as pozzolana, 141.
Standard aggregate, 15.
—— sands, 14.
Steel, Cover of, in reinforced work, 232.
Stone sand, 120.
Stones, Results of tests on, 108.
Storage of aggregate, 122.
—— — aluminous cement, 48, 50,
—— — cement, 34,

Storage of cement and setting time, 35.
—— — —— for long periods, 36.
Store for cement, 36.
——, Rules for cement, 37.
Strength of aluminous cement, 48, 49.
—— — cement, 14.
—— — concrete, 3.
—— — —— and diatomaceous earth, 145.
—— — rapid-hardening Portland cement, 41.
Stresses, Ministry of Transport working 41.
" Striked " bushel, 192.
Sugar, Effect of, 162.
Sulphate, Effect of, 161.
Sulphide in slag, 64.
Sulphur in breeze and clinker, 67.
" Super " cement, 55.

T

TANNIC acid, Effect of, 163.
" Tarvia " and curing, 237, 238.
Temperature and setting, 19.
—— — water ratio, 177.
Tensile strength of Portland cement, 7.
Test for clay, 98.
—— specimens and water ratio, 179.
Testing of cement, 8.
Tests for aggregates, 107.
—— — ——, Cost of, 107.
—— — aluminous cement, 48.
—— — cement, 7.
—— — ——, Quantities, 9.
—— — pigments, 134.
—— — wear, 85.
Tiles, Crushed, as pozzolanas, 141.
Time of mixing, 205, 207, 233.
Trap-rock, 65.
Trass, 139, 140, 147.
Tripoli as pozzolana, 140.
Types of aggregates, 59.
—— — pozzolanas, 140.

U

ULTRAMARINE blue, 133.
Under-burning of clinker, 23.
" Universal " cement, 189.

V

VENETIAN red as pigment, 133.
Vicat test for setting, 18, 19.
Voids in aggregate, 99, 100, 103.
—— — ——, Determination of, 101.
Volume change and pigment, 136.

W

WASHING soda as admixture, 156.
Water and strength, 166.
—— — workability, 218.
—— content, 165.
—— curing, Hot, 242.
——, Distilled, 158.
—— for hydration, 190.
——, Mixing, 158.
——, Moorland, 160.
——, Quality of, 158.
——, Quantity of, 189.
—— ratio, 233.
—— —— and aggregates, 171, 178.
—— —— — cement, 174.
—— —— — flexural strength, 182.
—— —— — high early strength, 187.
—— —— — sand content, 83.
—— —— — temperature, 177.
—— —— — test specimens, 179.
—— —— by volume, 168.
—— —— — weight, 168.
—— ——, Effective, 169.
—— —— theory, 73, 165, 167.
——, Sea, 162.
——, Specification for, 158.
Water-cement ratio theory, Abrams', 167.
Waterproofing admixtures, 156.
—— with iron, 153.
Wear, French coefficient of, 86.
—— of aggregates and concrete, 85.
——, Tests for, 85.
—— tests on concrete, 93.
Weather and pigment, 135.
Weighing aggregate, 195.
Weight of aggregate, 99, 103.
—— — broken stone, 103.
—— — cement, 10, 29.
—— — granite, 102.
Whinstone, 65.
White aggregate, 52.
—— cement, 2, 132.

White cement, Aggregate for, 52.
—— ——, Cost of, 51.
—— Portland cement, 51.
Winter work, 231.
Workability, 216, 233.
—— and admixtures, 219.
—— and aggregates, 78, 219.
—— and limestone, 222.
—— and mixing, 203.
—— and water, 218.
——, Measurement of, 222.
Working stress, 3.
—— ——, Ministry of Transport, 41.
Workmen for key positions, 233.

Y

Yellow ochre, 133, 134.
—— pigment, 134.
Yield, 76.

Z

Zinc carbonate in spar, 119.
—— chromate as pigment, 134.
—— compounds in spar, 64, 119.
—— oxide in spar, 119.
—— sulphide in spar, 119.
—— yellow, 134.